1974

Formulation and comparison of instantaneous distortion indices for assessing compressor stall.

Vann, John Lloyd.

FORMULATION AND COMPARISON OF INSTANTANEOUS DISTORTION INDICES FOR ASSESSING COMPRESSOR STALL

John Lloyd Vann

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

FORMULATION AND COMPARISON OF
INSTANTANEOUS DISTORTION INDICES
FOR ASSESSING COMPRESSOR STALL

by

John Lloyd Vann

June 1974

Thesis Advisor: Allen E. Fuhs

Approved for public release; distribution unlimited.

SECURITY CLASSIFICATION OF THIS PAGE (When Date Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
FORMULATION AND COMPARISON OF INSTANTANEOUS DISTORTION INDICES FOR ASSESSING COMPRESSOR STALL

5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis
June 1974

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
John Lloyd Vann

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93940

12. REPORT DATE
June 1974

13. NUMBER OF PAGES
102

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)
Naval Postgraduate School
Monterey, California 93940

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Vorticity; Compressor Stall; Distortion Index;
Instantaneous Distortion Indices

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
This thesis examines the problem of predicting distortion induced stall in an axial flow compressor. Three instantaneous distortion indices are used on the data presented. The data consist of eleven stall events run at 2.5 Mach by NASA Lewis on a J85-GE-13 turbojet engine. The three indices used include two indices based on vorticity and developed at the Naval Postgraduate School. The third index was developed

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601 |
(Page 1)

SECURITY CLASSIFICATION OF THIS PAGE (When Date Entered)

Block 20 - ABSTRACT (Cont.)

by Pratt and Whitney and is based on total pressure distributions. The three indices are compared by visual means using computer plots and are also compared by using a simple statistical approach. The computer program used was first developed by Shoemaker in his Master's thesis. The program is expanded in this thesis to compute and compare the three indices.

Formulation and Comparison of Instantaneous Distortion Indices for Assessing Compressor Stall

by

John Lloyd Vann
Lieutenant, United States Navy
B.S., Naval Postgraduate School, 1973

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1974

ABSTRACT

This thesis examines the problem of predicting distortion induced stall in an axial flow compressor. Three instantaneous distortion indices are used on the data presented. The data consist of eleven stall events run at 2.5 Mach by NASA Lewis on a J85-GE-13 turbojet engine. The three indices used include two indices based on vorticity and developed at the Naval Postgraduate School. The third index was developed by Pratt and Whitney and is based on total pressure distributions. The three indices are compared by visual means using computer plots and are also compared by using a simple statistical approach. The computer program used was first developed by Shoemaker in his Master's thesis. The program is expanded in this thesis to compute and compare the three indices.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

The author wishes to thank Professor Allen E. Fuhs of the Naval Postgraduate School at Monterey Calif. His endless flow of ideas, professional guidance, and refreshing sense of humor have truly made this thesis possible.

The author also wishes to thank Mr. Paul Burstadt of the NASA Lewis Research Center in Cleveland, Ohio. Mr. Burstadt has certainly gone out of his way to provide information and data for the preparation of this thesis.

I. INTRODUCTION

This paper addresses the problem of distortion-induced or drift stall in an axial flow compressor. The problem is a current one in industry and has not been wholly resolved. The present method of dealing with the problem of distortion is to operate axial flow compressors with a sufficient stall margin to avoid the problem altogether, but this is an expensive procedure. Best engine efficiencies are obtained by operating close to the stall or surge line. By providing a large stall margin, we are in effect sacrificing performance via reduced efficiencies. The problem is especially germane to military aircraft. The normal operating conditions of military aircraft include hard maneuvering, high "g" flight, steam ingestion from aircraft carrier launches, and exhaust gas ingestion from forward firing weapons. These operating regimes cause a pressure, temperature, and gaseous molecular weight distortion of the flow entering the compressor section of the engine.

In order to deal with distortion, it is first necessary to find or define an adequate measure of it. A distortion index based on steady-state or long-time averaged values of distortion has been attempted. This method has met with some degree of success, but it is apparent that peak instantaneous distortions of sufficient magnitude can induce stall when the time averaged distortion factor remains relatively low. The current approach and the approach of this paper is to

examine distortion as an unsteady phenomenon and to measure distortion over time intervals comparable with the characteristic times of an axial compressor.

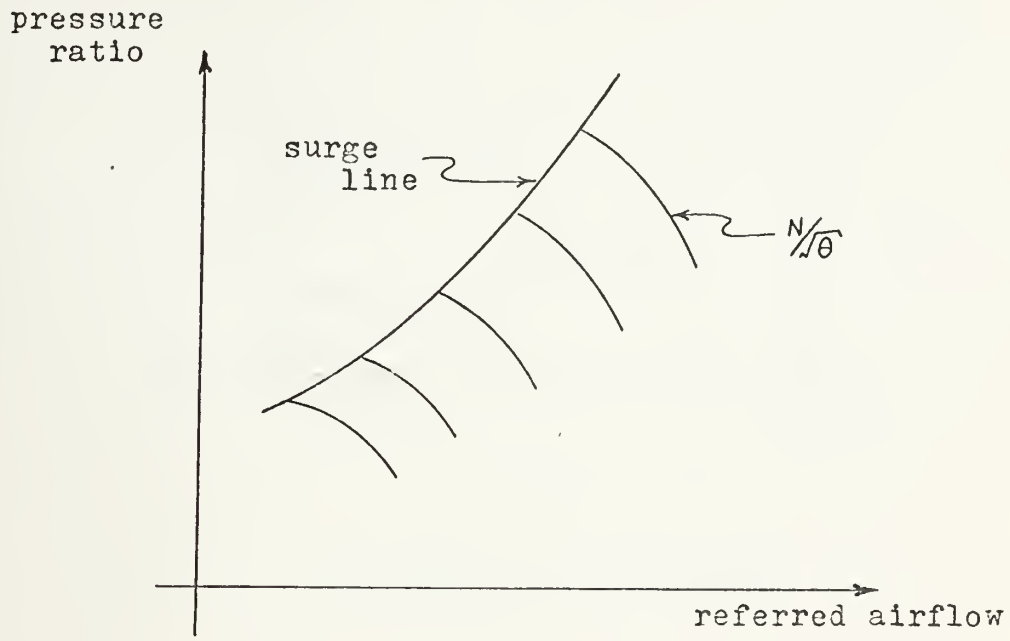
A computer program was first developed by Ens. Shoemaker [ref 3] utilizing an existing interpolation scheme developed at the Lewis Research Center of NASA. The program calculates the total pressure distribution just prior to the compressor section of a J85-GE-13 turbojet engine as a function of time. The program also utilizes the theory of Fuhs, Farmer, and Iverson [ref 1, ref 2] to compute the circumferential and radial components of vorticity across the face of the compressor section as a function of time. The computer program was extended for this paper to calculate and statistically compare two existing distortion indices plus an additional index developed by Downs and studied in this thesis [ref 4]. This procedure was applied to eleven stall events recorded and analyzed by the NASA Lewis Research Center [ref 5].

II. NATURE OF THE PROBLEM

A. COMPRESSOR SURGE

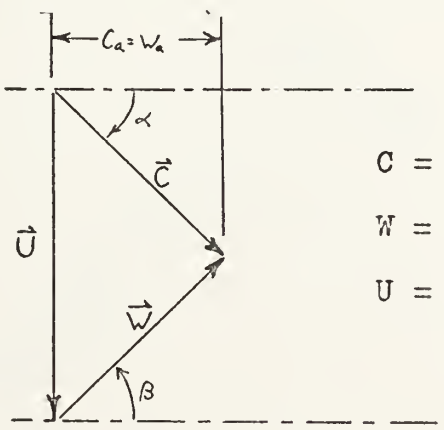
The line marked "surge" in figure 1 denotes the locus of unstable operation points for an axial compressor. The cause of compressor surge may be visualized in the following manner. At any given reference RPM ($N/\sqrt{\theta}$) and blade radius, a rotor speed U is specified. Consider the velocity diagram in figure 2. A reduction in referred mass flow rate will cause a reduction in the axial component of velocity. Since the rotor speed is fixed, an increase in the relative flow angle β will occur. Present compressor design incorporates a fixed rotor geometry and thus the relative flow angle may only increase to a maximum value which is dependent on blade design.

An insight into the unstable nature of the surge line may be made by comparing the characteristics of the compressor to the characteristics of a throttle. A throttle is set to produce a certain back or receiver pressure, given an inlet pressure. We may visualize a system consisting of a compressor producing a high inlet pressure followed by a throttle which dumps the high compressor air to ambient conditions (fig 3). A plot of the characteristics of the hypothetical throttle and compressor are included in figure 4. The compressor is represented at a fixed reference RPM. The dashed lines represent fixed throttle settings. Selecting a particular throttle setting determines two possible



Compressor Characteristics

FIGURE 1



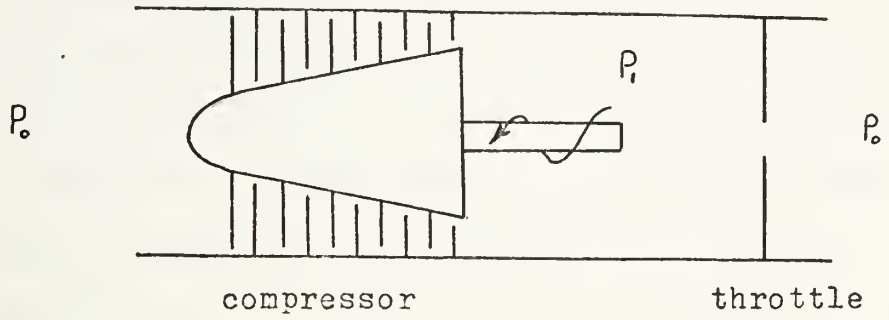
C = absolute velocity

W = relative velocity

U = rotor velocity

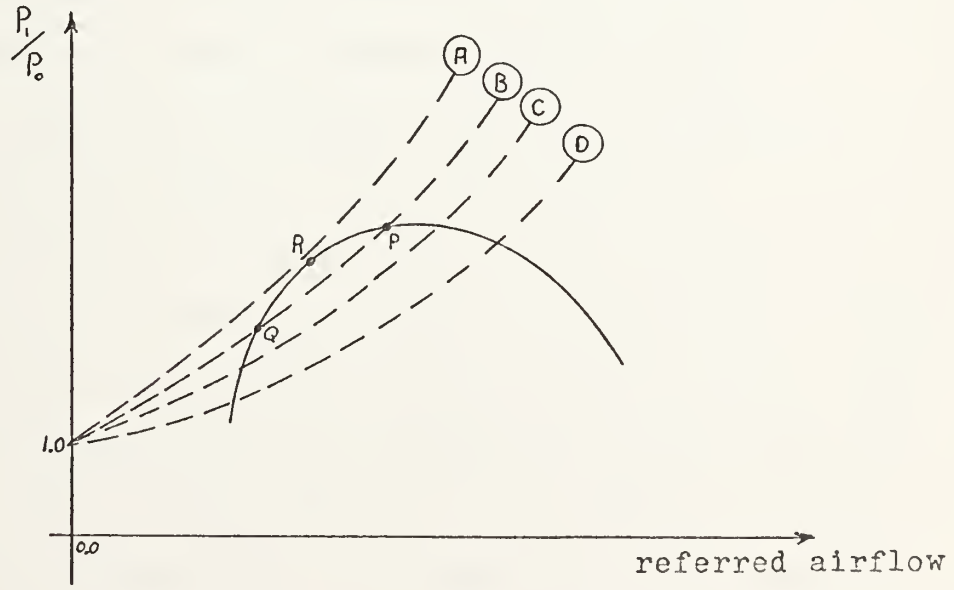
Velocity Diagram

FIGURE 2



Compressor-Throttle System

FIGURE 3



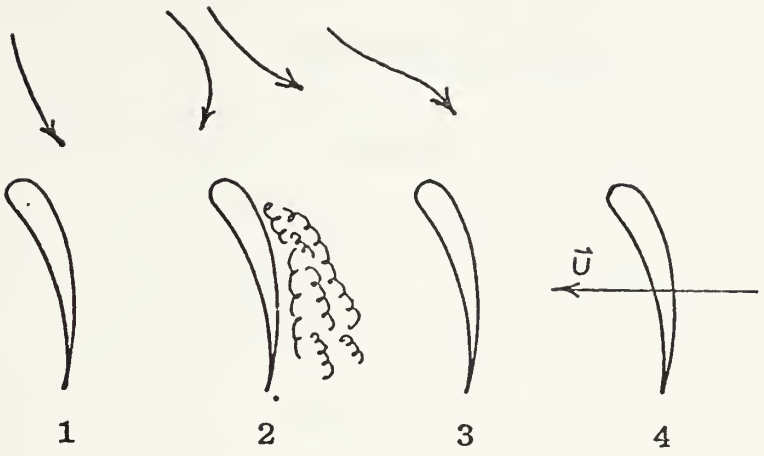
Characteristics Plot

FIGURE 4

compressor points. Consider as a throttle setting line B, with possible operating points P and Q. First consider point P. If the mass flow rate is perturbed to a higher mass flow rate, the throttle setting will demand a higher pressure ratio, whereas the compressor produces a lower pressure ratio. In this case the combination of compressor and throttle will return to point P. Conversely a lower flow rate will cause the throttle to demand a lower pressure ratio whereas the compressor will produce a higher ratio. Again the system will be forced to return to point P. Consider now point Q. A slight perturbation mass flow will produce problems. The system is free in this case to follow any perturbations and the system is unstable. Neutral stability is represented by point R where the slope of the throttle curve matches the slope of the compressor curve.

B. CLEAN STALL VERSUS DISTORTION INDUCED STALL

The surge line in figure 1 denotes the conditions at which stall will occur if the inlet velocity profile is uniform, producing a uniform total pressure distribution. In actuality, the velocity profile is not uniform and pressure perturbations may produce a local condition over a small region of the compressor face which will cause stall over that region. This stalled region in turn produces a condition known as rotating stall. In figure 5, if the conditions are such that blade 2 becomes stalled, the effective flow area between blades 2 and 3 is reduced. This reduction in flow



Rotating Stall

FIGURE 5

area causes a flow diversion which tends to overload and stall blade 3. Continuation of this process will produce rotating stall. It is noteworthy that rotating stall propagates in the opposite direction from rotor velocity at about half rotor speed. Rotating stall may develop into surge or fully developed stall.

It is apparent that the instantaneous velocity distributions across the compressor face may cause stall when the steady-state conditions are below the surge line. This velocity distribution in turn produces a total pressure distribution which is the form of the data examined in this thesis.

III. DISTORTION INDICES

A. VORTICITY VIA CROCCO'S THEOREM

Non-dimensional vorticity components in both the circumferential and radial directions of a cylindrical coordinate system may be calculated using the theory of Fuhs, Farmer and Iverson [ref 1, ref 2]. Starting with Crocco's Theorem and using an order of magnitude analysis, it was possible to reduce the expression for these parameters to:

$$\omega'_\theta = \frac{-1}{\gamma P' U'_z} \frac{\partial P'}{\partial r'} - \frac{M}{2} \frac{\partial T'}{\partial r'} \quad ; \quad \omega'_r = \frac{1}{\gamma P' r' U'_z} \frac{\partial P'}{\partial \theta} + \frac{M}{2r'} \frac{\partial T'}{\partial \theta}$$

where:

$$P' = \frac{P_T}{\bar{P}_T} \quad ; \quad \omega'_\theta = \frac{\omega_\theta D}{2\bar{a}} \quad ; \quad r' = \frac{2r}{D} \quad ; \quad U'_z = \frac{U_z}{\bar{a}} \quad ; \quad T' = \frac{T_T}{\bar{T}_T}$$

For a detailed explanation, consult reference 1. The calculations are examined more briefly in reference 2.

Analytical studies and data analysis have been performed in an attempt to relate the effects of total temperature and total pressure distortions on compressor performance [ref 7]. The vorticity approach is well suited to this problem, as both total temperature and total pressure may be taken into account in the calculations of vorticity. It would be beneficial to examine data which consist of both temperature and pressure patterns across the compressor face. Additional work in this area would be helpful. The data examined in this thesis, however, did not present a significant temperature gradient and the expressions for vorticity could be

reduced to:

$$\omega'_\theta = \frac{-1}{\gamma P' U'_z} \frac{\partial P'}{\partial r'} \quad ; \quad \omega'_r = \frac{1}{\gamma P' r' U'_z} \frac{\partial P'}{\partial \theta}$$

The task of this thesis was to determine whether an index based on vorticity would provide a meaningful prediction of compressor stall. Two such indices based on vorticity are examined in this thesis. The first index was proposed by Shoemaker [ref 3] and is based on circumferential vorticity. A second index proposed by Downs [ref 4] and based on both radial vorticity and total pressure is examined. In order to provide a means of comparison, a third index based on total pressure and taken from Zonars [ref 8] was also examined.

B. SHOEMAKER INDEX

James E. Shoemaker approached the problem of finding a vorticity based index by first printing out maps of pressure, circumferential vorticity and radial vorticity. In order to accomplish this goal he utilized a set of subroutines developed at Wright Patterson Air Force Base, and altered them to print out the maps at times near stall and at times far from stall, to provide a comparison. A copy of his computer program is included at the end of his Master's thesis [ref 3]. Using this procedure, Shoemaker found a vorticity pattern that frequently occurred within twenty-five milliseconds of stall, and was not common at other times. The pattern was characterized by a ring of large negative circumferential vorticity at the midspan of the compressor face, and a large positive ring at the tip. He developed an index based on

this pattern which will be referred to as the Shoemaker index. He divided the compressor face into three concentric regions. Region one at r' less than 0.5 was ignored. Region II was established as that area between radii of 0.55 and 0.70. Region III was that area between radii of 0.8 and 0.95. The Shoemaker index then summed over Region II but set any positive circumferential vorticity equal to zero. Likewise Region III was summed where any negative vorticity was set equal to zero. The instantaneous Shoemaker index was set equal to the sum of the absolute value of the two summations. In notation form,

$$\text{Shoemaker Index (T)} = \frac{1}{N} \Sigma \left[\omega_\theta^+\right] - \frac{1}{N} \Sigma \left[\omega_\theta^-\right]$$

where ω_θ^+ = positive values of circumferential vorticity in Region III

ω_θ^- = negative values of circumferential vorticity in Region II

In order to take into account the added effect of the duration of the pattern, Shoemaker set his final index equal to the product of three consecutive instantaneous indices described above. This latter procedure was not used in the present thesis. The Shoemaker index as used herein thus refers to the instantaneous index and is an indication of distortion in the radial direction.

The Shoemaker index has one real advantage when the transport time from the measuring probes to the compressor stage (where stall originates) is considered. The pattern

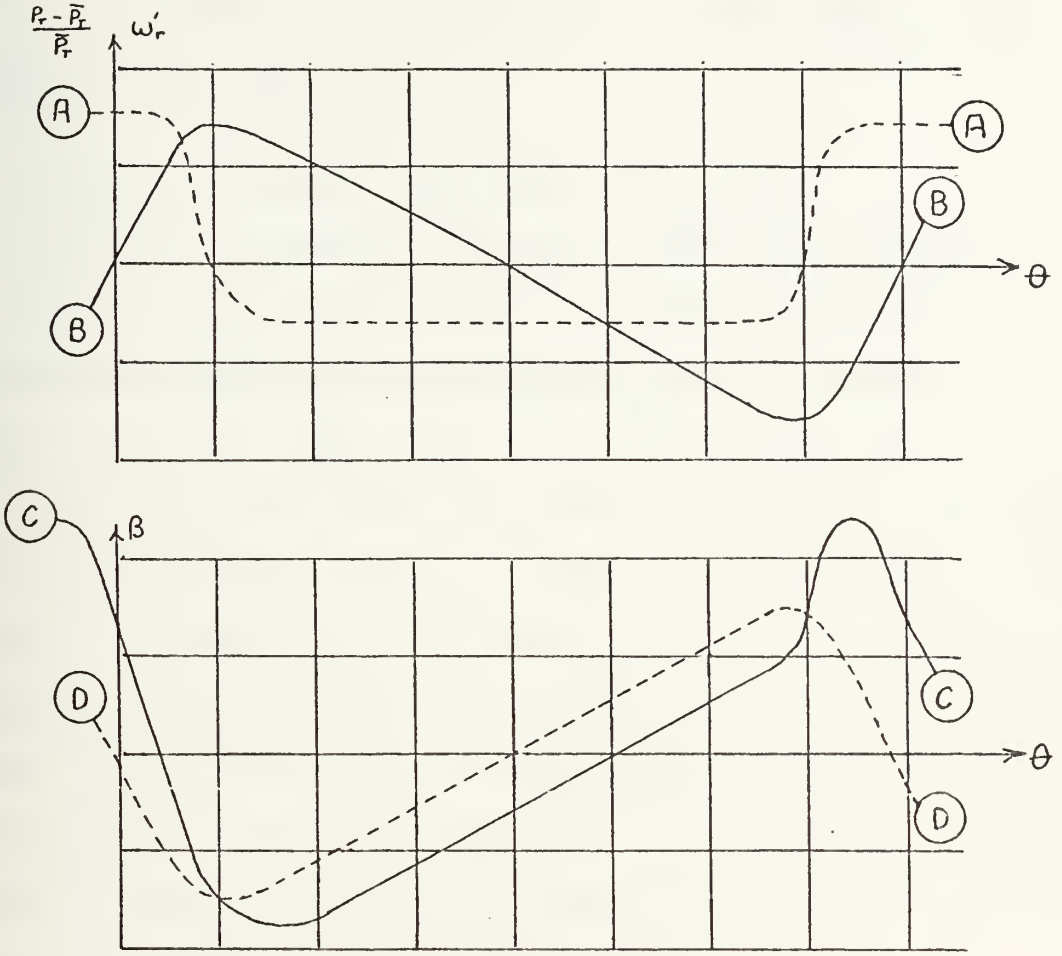
develops at a time before stall which is larger than the transport time from the measuring probes to the stall region. This could be very useful if variable stators or the fuel control were available to avert stall.

C. DOWNS INDEX

A second index which was proposed by Downs [ref 4] was formulated and is explored in this thesis. This index incorporates both total pressure and radial vorticity. The basic idea was to consider the contribution of both total pressure and vorticity to the relative flow angle β. Increasing β would cause the rotor blade incidence angle to increase and would tend to load the blade. A perturbation plot of β versus θ, where the deviation of β from the reference line takes into account pressure and vorticity effects, is shown in figure 6. The corresponding plot of total pressure and ω_r' is also shown. The reference line represents uniform flow. It can be seen that although ω_r' is dependent upon the pressure gradient, the combined effect of pressure and ω_r' on β is dependent on both the gradient and relative magnitude of pressure. The Downs index was formulated to search the compressor face for the largest value of the combined effect of pressure plus ω_r' over any 60 degree sector. In notation form,

$$\text{Downs Index (t)} = \Sigma \left[\frac{\overline{P}_T - P_T}{\overline{P}_T} + \omega_r'\right]_{\max 60}$$

where $\overline{P}_T$ = average total pressure over entire face of compressor at time t



A = possible ω'_r

B = corresponding $\frac{P_r - \bar{P}_r}{\bar{P}_r}$

C = $\frac{P_r - \bar{P}_r}{\bar{P}_r}$ plus ω'_r effect on β

D = $\frac{P_r - \bar{P}_r}{\bar{P}_r}$ effect on β

θ measured in direction of rotor rotation

Effect of pressure and radial vorticity on β

FIGURE 6

The Downs index is primarily an indication of distortion in the circumferential direction. For a more complete analysis, consult Downs [ref 4].

D. PRATT AND WHITNEY K_{DM} DISTORTION INDEX

In order to provide a means of comparison between vorticity based indices and an index calculated directly from total pressures, the Pratt and Whitney K_{DM} index was selected from Zonars [ref 8]. This index was selected primarily because of case four, which was one of the eleven cases investigated. Distortion indices are plotted for all eleven cases in Appendix A. Neither of the vorticity indices had satisfactorily predicted stall in case four; from examining the pressure maps, K_{DM} appeared to be an appropriate index. The K_{DM} index was applied to case four and to all other cases. This index was developed by Pratt and Whitney for the TF-30 installed in the F-111A aircraft and is defined as follows:

$$K_{DM} = \frac{\frac{1}{2} \Sigma \left[\frac{P_{Tmax} - P_{Tmin}}{P_{Tave}}\right]_i \bar{\theta}_i C_i}{\Sigma C_i} \times 100$$

where C = ratio of compressor inlet radius to ring radius

i = number of ring

$\bar{\theta}$ = largest continuous arc of the ring over which the total pressure is below the ring average pressure

P_{Tmax} = ring maximum total pressure

P_{Tave} = ring average total pressure

P_{Tmin} = ring minimum total pressure

It can be seen that the K_{DM} index is an indication of distortion in the circumferential direction and puts more emphasis on the region near the hub. It would be expected that the K_{DM} index and the Downs index would be comparable since both search for circumferential distortion. This was in fact the case and will be discussed in a later section.

IV. EXPLANATION OF DATA

The NASA Lewis Research Center conducted an experimental wind-tunnel investigation to determine the effects of time-varying total-pressure distortions produced in a supersonic inlet on a J85-GE-13 turbojet engine [ref 5]. Selected data taken during this investigation were digitized on magnetic tape; the latter is the source of data used in this thesis. The following explanation of data is largely a brief summary of the explanation presented by Burstadt and Calogeras [ref 5] and is given here to provide an overall understanding of the data analysis.

The inlet was an axisymmetric mixed-compression type. The compressor was an eight-stage axial flow compressor with interstage bleed and variable inlet guide vanes. An afterburner section was present but was not used during the test procedure. The engine bleed system was modified to make the compressor operate with less than normal stall margin. The following excerpt is quoted from reference 5:

> The test procedure was to establish an engine operating condition in the vicinity of the compressor stall point. The FM tape recorder was started and a steady-state data scan was made. Then, while the FM tape recorder was still running, the compressor pressure ratio was increased slightly and the throttle adjusted to maintain a constant rotor speed. If stall did not occur, this procedure was repeated until the stall event was recorded on the FM tape. In some cases the stall occurred after the engine had stabilized at an equilibrium operating condition. These were called 'drift' stalls.

All eleven of the stalls examined in this thesis were of the "drift" type. NASA Lewis considered only seven of the eleven cases in their analysis. Cases 6, 8, 9, and 10 were excluded on the grounds either that their causes were attributable to steady-state distortion levels or that they showed very little loss in stall margin. Table I shows steady-state operating conditions for all eleven cases presented in this thesis. The NASA Lewis analysis identifies each case number as a steady-state reading number. These NASA identifying numbers are included in Table I for comparison [ref 5].

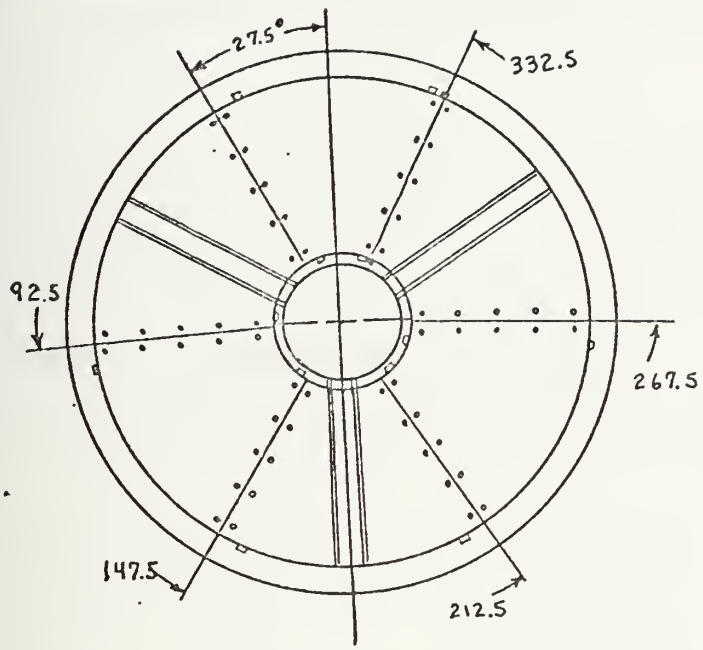
Steady-state and dynamic pressure instrumentation at the compressor face is shown in figure 7. Only the fluctuating component of pressure was recorded from each of the dynamic probes. Absolute pressures were later obtained by adding the fluctuating component to the steady-state value.

Frequency response of the dynamic probes was flat to about 2000 hertz. The fluctuating signal from each pressure transducer was recorded on FM multiplexed tape at 152.4 centimeters per second. The data in a 225 millisecond period just prior to stall were digitized at an effective rate of 8000 points per second per channel. These data when processed by the computer program listed in the back of this thesis provided the distribution of total pressure across the compressor face with a time spacing of 0.125 milliseconds between distributions. The distributions of total pressure were further processed to provide distributions of both circumferential and radial vorticity as a function of time. In order to

TABLE I

STEADY-STATE OPERATING CONDITIONS

CASE NO.	NASA IDENT NO.	M_o	P_o (psfa)	$\frac{\bar{P}_3}{\bar{P}_2}$	$\frac{N*100}{N*\sqrt{\theta}}$	W_{corr} (lb/sec)	$\frac{\bar{P}_2}{P_o}$	$\frac{\Delta \bar{P}_{rms}}{\bar{P}}$	α (deg.)
1	154	2.50	1968.5	5.240	92.25	38.5	.799	.0691	0
2	162	2.58	1968.4	5.288	92.89	39.5	.769	.0460	5
3	141	2.50	1966.6	7.045	98.82	42.6	.761	.0851	0
4	148	2.50	1966.2	4.601	86.88	34.2	.788	.0658	0
5	164	2.58	1967.4	4.388	86.89	34.9	.843	.0185	5
6	82	2.58	1965.2	4.784	86.34	34.0	.854	.0156	5
7	103	2.68	1972.3	4.684	86.42	33.7	.736	.0500	0
8	200	2.50	1970.5	6.808	95.98	41.0	.768	.0275	0
9	214	2.50	1971.7	5.341	87.29	32.8	.739	.0209	0
10	219	2.50	1958.8	5.812	89.93	35.3	.794	.0167	0
11	261	2.58	1972.5	4.355	87.00	34.8	.783	.0209	6



Compressor Face

FIGURE 7

reduce the amount of calculating involved, only one out of five readings was actually processed so that there was five times 0.125 or 0.625 milliseconds of time between readings actually processed.

The determination of stall time was made by NASA Lewis. The signals from the compressor static pressure transducers were put on strip charts and examined by NASA. For all cases, the row of instrumentation at the 290 degree location showed the earliest indication of stall. Since the origin of stall in a compressor stage causes an abrupt loss in the airflow pumping of that stage, a compression wave is

propagated upstream. This compression wave is referred to as a hammershock. The following excerpt is quoted from reference 5:

> Because there were only two axial rows of instrumentation inside the compressor, it was not possible to determine exactly when stall originated inside the compressor. Although the first indication was seen at the 290 degree location, a stall zone could originate just past the 45 degree location but not be detected until it rotated past the instrumentation at 290 degrees. Since the stall zone rotated at about half rotor speed (8 msec/rev) there could be as much as a 6-millisecond delay before it was detected at the 290 degree location.

A one-millisecond period for transport time between sensors and stall stage, plus time for blade response, was predicted by NASA. This produces a six-plus-one or seven-millisecond possible time lag between actual initialization of stall and the stall time listed in this thesis.

V. THREE INDICES APPLIED TO DATA

A. EXAMINATION PROCEDURE

The computer program first developed by Shoemaker [ref 3] was adapted to compute each index as a function of time for the entire time interval provided by NASA Lewis. This time interval varied slightly but was generally about 215 milliseconds of data prior to first indication of stall. The DRAW subroutine of the Naval Postgraduate School was used to plot each index. These plots are included in Appendix A and are plots of the instantaneous version of each index. A numerical printout was also provided by the program. A sample numerical printout for the Shoemaker index case one is included at the end of this thesis. Table II provides an explanation of the terms for the numerical printout.

In addition to the computer plots, which may be used to determine if the given index is an accurate predictor of stall, a simple statistical approach was used. After the first fifty values of the index were computed, the mean and standard deviation for those fifty values were obtained. Then, as the next fifty values of the index were computed, the following test was made. If the average of the three previous values of the index at any time exceeded a certain criterion value, the computer program printed out a stall warning with the time in milliseconds of occurrence. The criterion level was set in the following manner:

$$\text{Test} = \text{mean} + 2.5 \times \text{standard-deviation}.$$

TABLE II

EXPLANATION OF PROGRAM TERMS

N	=	index number (a function of time).
FACT(N)	=	value of instantaneous index at time "N".
DFACT(N)	=	average of three previous FACT(N) values.
TIME	=	"N" time in milliseconds. Starts at zero for each new case.
PTAVE	=	average total pressure over compressor face at time "N".
MEAN	=	mean value of FACT(N) for 50 previous values of N, when not zero.
STD-DEV	=	standard deviation of FACT(N) for 50 previous values of N, when not zero.

At the end of each 50 values of the index, a new mean and standard-deviation were computed and the test criterion was established for the next 50 values of the index. This simple test was used on all thirty-three runs made, and the results are summarized in the next section. Obviously, the test criterion could be lowered, with resulting greater occurrence of stall prediction, but this would also increase the number of false warnings. The value of test was initially set to predict stall for the K_{DM} index Case three without any false warnings. The test criterion could have been set to an optimum value for each particular index with possible better results but this method was not used. The same test was applied to all cases. The statistical method has the real advantage

of not being subject to interpretation. All thirty-three computer plots are included in this thesis, since they certainly are subject to personal interpretation as to the prediction of compressor stall.

B. COMPARISON OF RESULTS

There are two indicators of the results of the data reduction. First are the computer plots, which provide an eyeball examination of results. A matrix summation of the computer plot results is provided by Table III. The second method was the use of statistical mean and standard-deviation discussed in the preceding section. A matrix summation of the statistical method is provided by Table IV. In both tables, where stall was predicted, the time to stall is given in milliseconds.

There are several points of interest. As had been previously expected, there is some correlation between the K_{DM} index and the Downs index, since both rely on circumferential distortion. Using the statistical method, all of the cases predicted by the K_{DM} index were also predicted by the Downs index. The Downs index predicted two additional cases utilizing this method. Using the computer plot interpretation, the K_{DM} method predicts six cases and the Downs index predicts five, with four predictions common to both indices.

If one were to use a combination of both vorticity based indices, the statistical method would have predicted eight out of the eleven cases presented. Using this method there

TABLE III

COMPUTER PLOT SUMMARY

(based on visual interpretation)

RUN	PRATT & WHITNEY K_{DM} INDEX	SHOEMAKER INDEX	DOWNS INDEX
1	No Prediction	22.5 millisecs	23.0 millisecs
2	3.0 millisecs 3 same magnitude	25.0 millisecs	No Prediction one false peak
3	3.0 millisecs	21.0 millisecs 4 false peaks	6.0 millisecs 2 false peaks
4	4.0 millisecs 2 larger peaks	No Prediction	No Prediction one false peak
5	No Prediction	3.0 millisecs 2 smaller peaks	No Prediction
6	No Prediction	No Prediction	No Prediction
7	No Prediction	No Prediction	No Prediction
8	4.5 millisecs	No Prediction	2.0 millisecs
9	4.0 millisecs one false peak	16.0 millisecs 5 same magnitude	2.0 millisecs
10	4.0 millisecs	No Prediction	2.0 millisecs
11	No Prediction	6.0 millisecs 2 larger peaks	No Prediction
totals	6 Predictions	6 Predictions	5 Predictions

TABLE IV

STATISTICAL SUMMARY

RUN	PRATT & WHITNEY K INDEX	SHOEMAKER INDEX	DOWNS INDEX
1	No Prediction	21.8 millisecs 1 false warning	22.28 millisecs 2 false warnings
2	No Prediction	23.9 millisecs	No Prediction 2 false warnings
3	0.9 millisecs	20.2 millisecs 1 false warning	4.88 millisecs 2 false warnings
4	No Prediction	No Prediction 1 false warning	No Prediction 1 false warning
5	No Prediction	No Prediction	No Prediction
6	No Prediction	No Prediction	No Prediction
7	No Prediction	No Prediction	19.88 millisecs 1 false warning
8	2.88 millisecs	No Prediction 2 false warnings	2.88 millisecs
9	0.4 millisecs	35.8 millisecs 2 false warnings	0.0 millisecs
10	1.62 millisecs	No Prediction 1 false warning	2.88 millisecs 1 false warning
11	No Prediction	11.8 millisecs	No Prediction
totals	4 Predictions	5 Predictions	6 Predictions

would have been seventeen false warnings. The number of false warnings could be reduced by a reduction in the test criterion to a point where no loss in stall prediction would occur.

There could be as much as seven milliseconds of time lag between actual stall time and predicted stall time. This presents a problem since the data could include the effects of the hammershock which occurs after stall, if the time lag is too great. It is certainly no problem to produce an index which will sense the hammershock and the question arises, did the index actually predict stall or were the effects of the hammershock being felt? By examining the numerical printout of average total pressure as a function of time and taking into account the possible seven-millisecond lag time, it was apparent that this could have been a problem in only four cases. These four cases should be held suspect and are cases 3, 8, 9, and 10. It is noteworthy that the Shoemaker index predicted stall in two of these four cases sufficiently far in advance to preclude the problem.

VI. CONCLUSIONS

An investigation into the problem of predicting compressor stall using instantaneous distortion parameters was made. Some success was evidenced by both the statistical method and computer plot interpretation, but it was not possible to predict stall in every case using one or any combination of the indices explored. This seems to indicate that an axial compressor is subject to many instantaneous distortion patterns as well as to steady-state distortion, whereas one index may only search for one category of distortion. If the cause of compressor stall was in every case instantaneous radial distortion over the outer portion of the compressor face, then in every case the Shoemaker index should predict stall. If the cause was in every case circumferential distrotion over some arbitrary sixty degree sector then the Downs index would be successful. If the distortion conforms to the ring pattern explored by the Pratt and Whitney index, then that method would succeed. In fact, it seems naive to believe that compressor stall could be predicted in every case using any one index. The indices explored in this thesis and the indices used by industry today may certainly be improved upon, but it is doubtful that any one index will prove to be a panacea.

In spite of the compound nature of compressor stall, instantaneous indices are useful. The Pratt and Whitney index used in this thesis was developed for the F-111A with a

specific inlet-engine combination. It is in that context that distortion parameters would appear most useful - that is, to examine an inlet-engine system for compatibility. The performance of an inlet-engine system which too often experiences one type of distortion pattern may be improved upon; distortion indices would be very useful in isolating a predominant pattern.

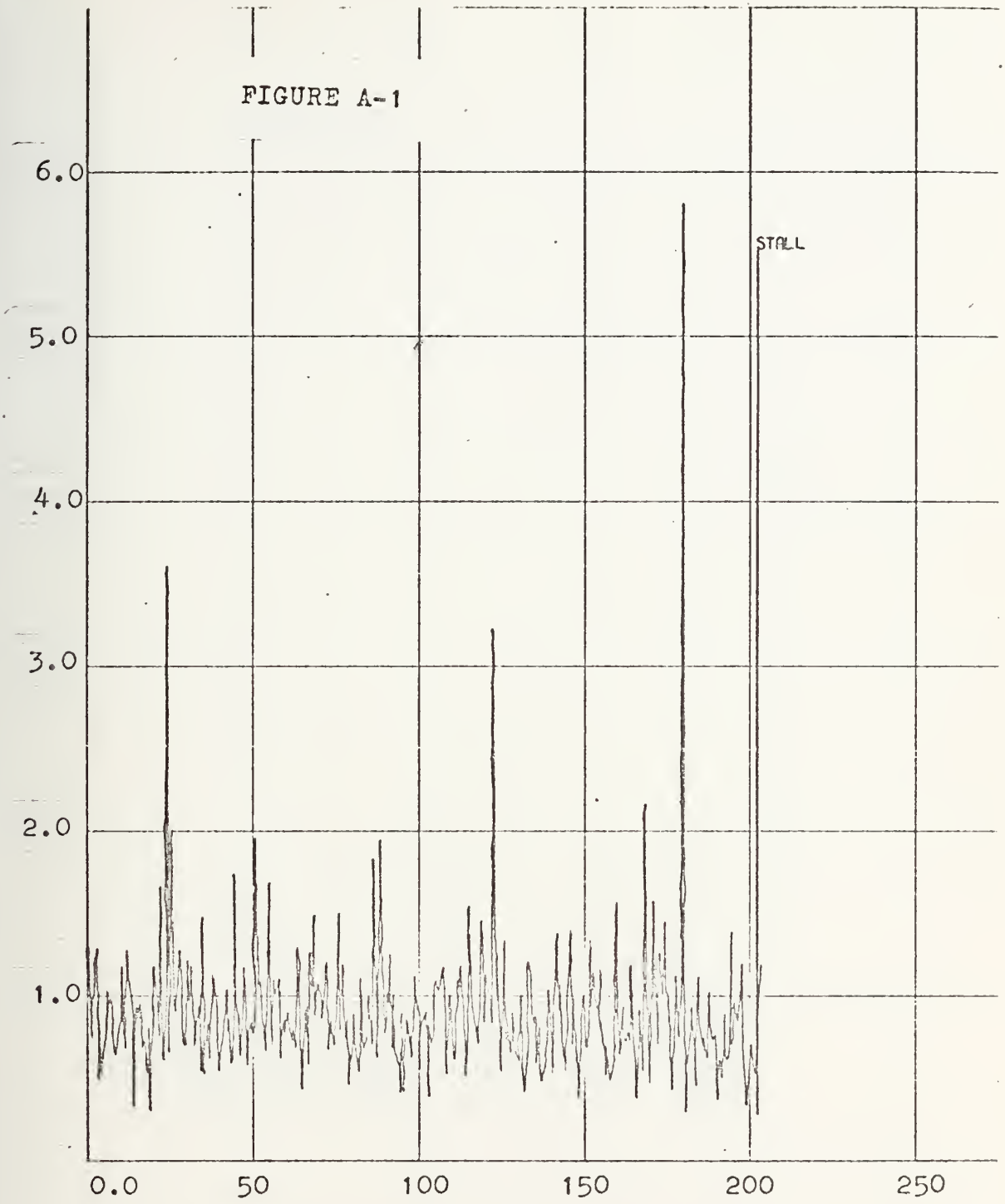
The use of vorticity as an index parameter has some real advantages. Both temperature and pressure gradients may be integrated into a single parameter. Vorticity may be visualized more simply and is a natural characteristic of the fluid. The Shoemaker index, when successful, harbingers stall sufficiently far in advance possibly to enable correction of the deficiency using engine controls. Vorticity appears to be a promising dimensionless parameter and deserves further investigation.

APPENDIX A

COMPUTER PLOTS

The following thirty-three computer plots provide the instantaneous version of each of the three indices considered. In all cases, the horizontal scale is read in milliseconds. The vertical scale gives the index value and is a non-dimensional number. No consideration was given to index magnitude in predicting stall. For any given case, a strong peak just before stall in relation to that particular case was considered to be sufficient for stall prediction.

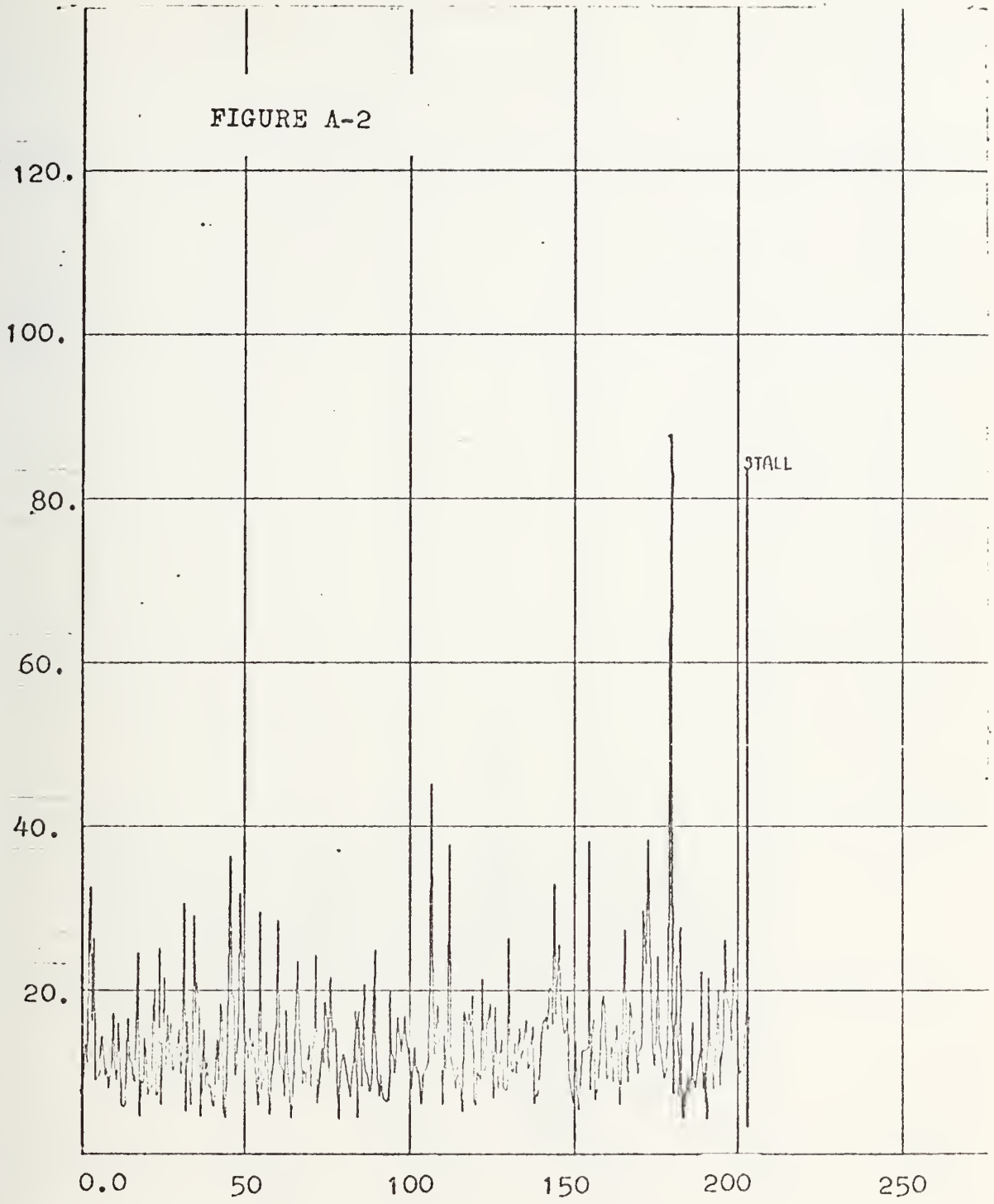
FIGURE A-1



Shoemaker Index

case one

index vs time in millisec

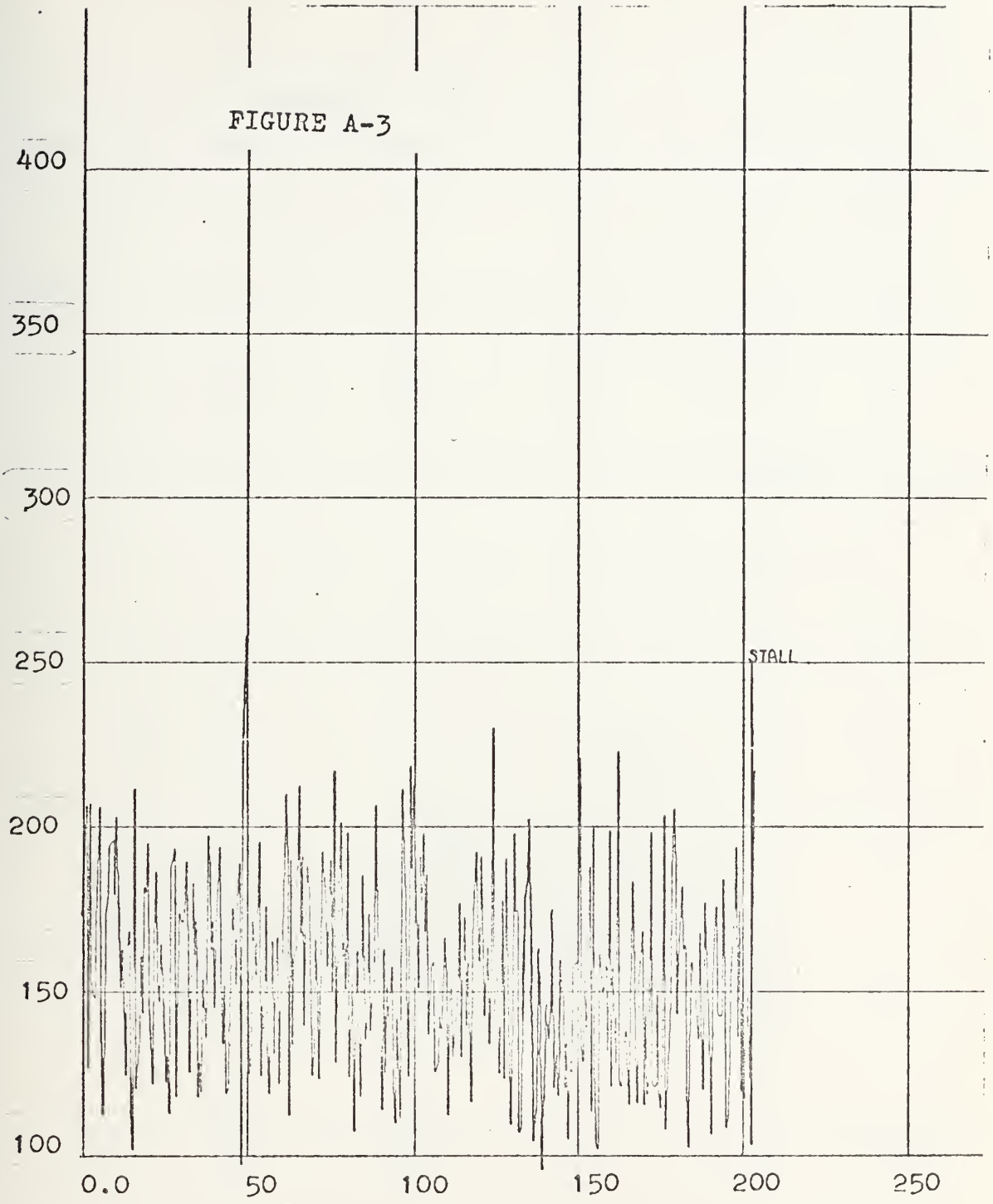


Downs Index

case one

index vs time in millisec

FIGURE A-3

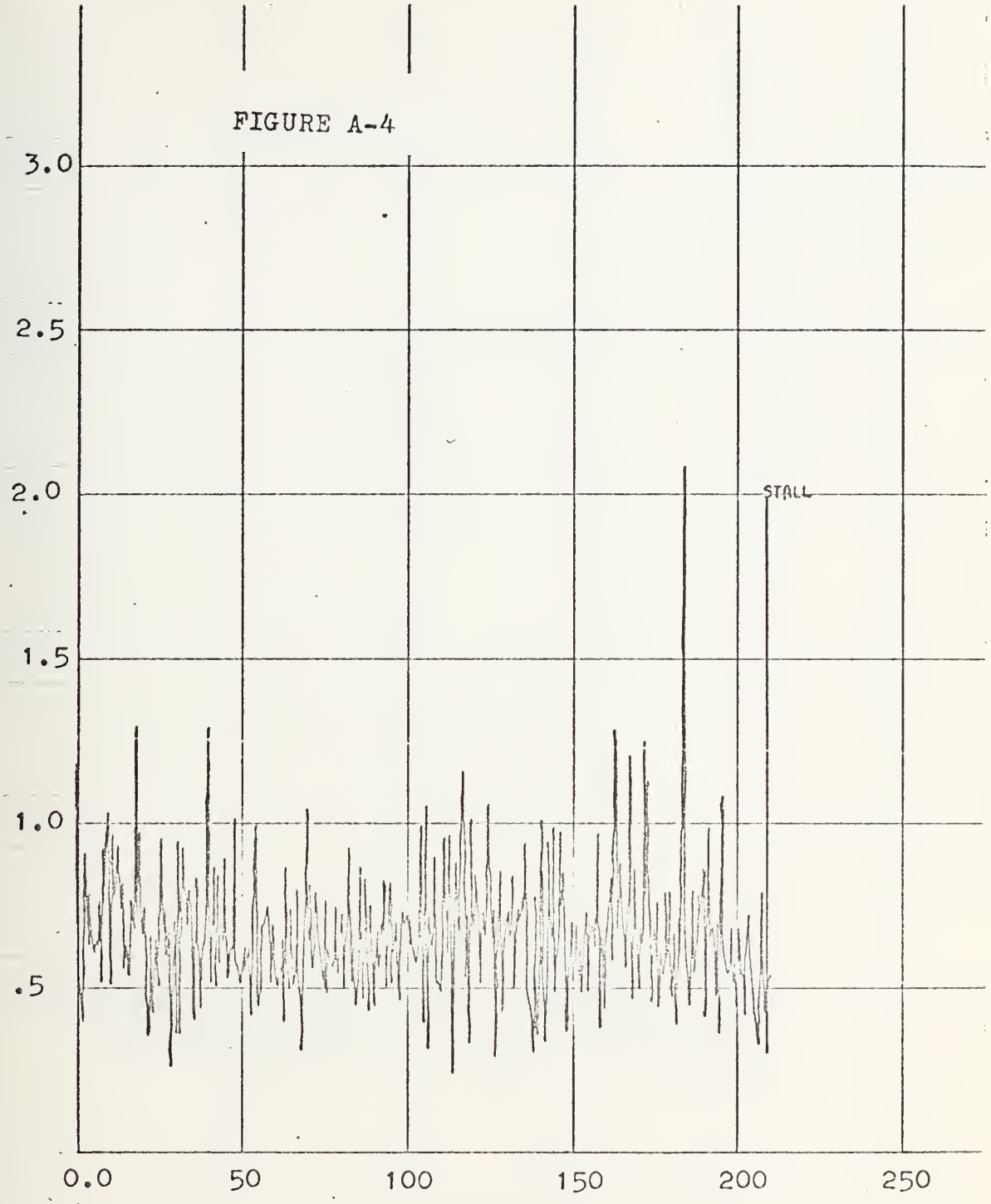


Pratt and Whitney Index

case one

index vs time in millisec

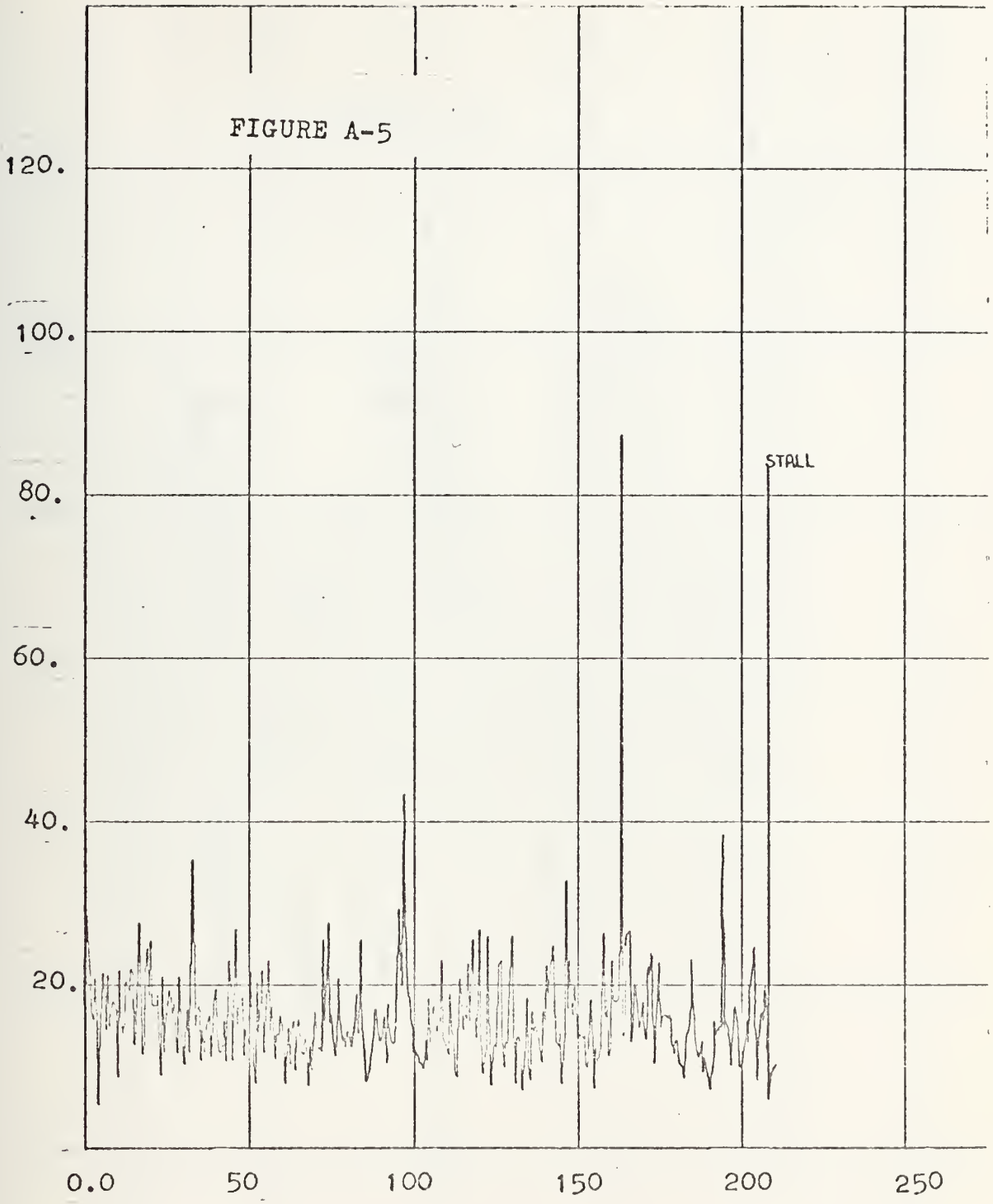
FIGURE A-4



Shoemaker Index

case two

index vs time in millisec

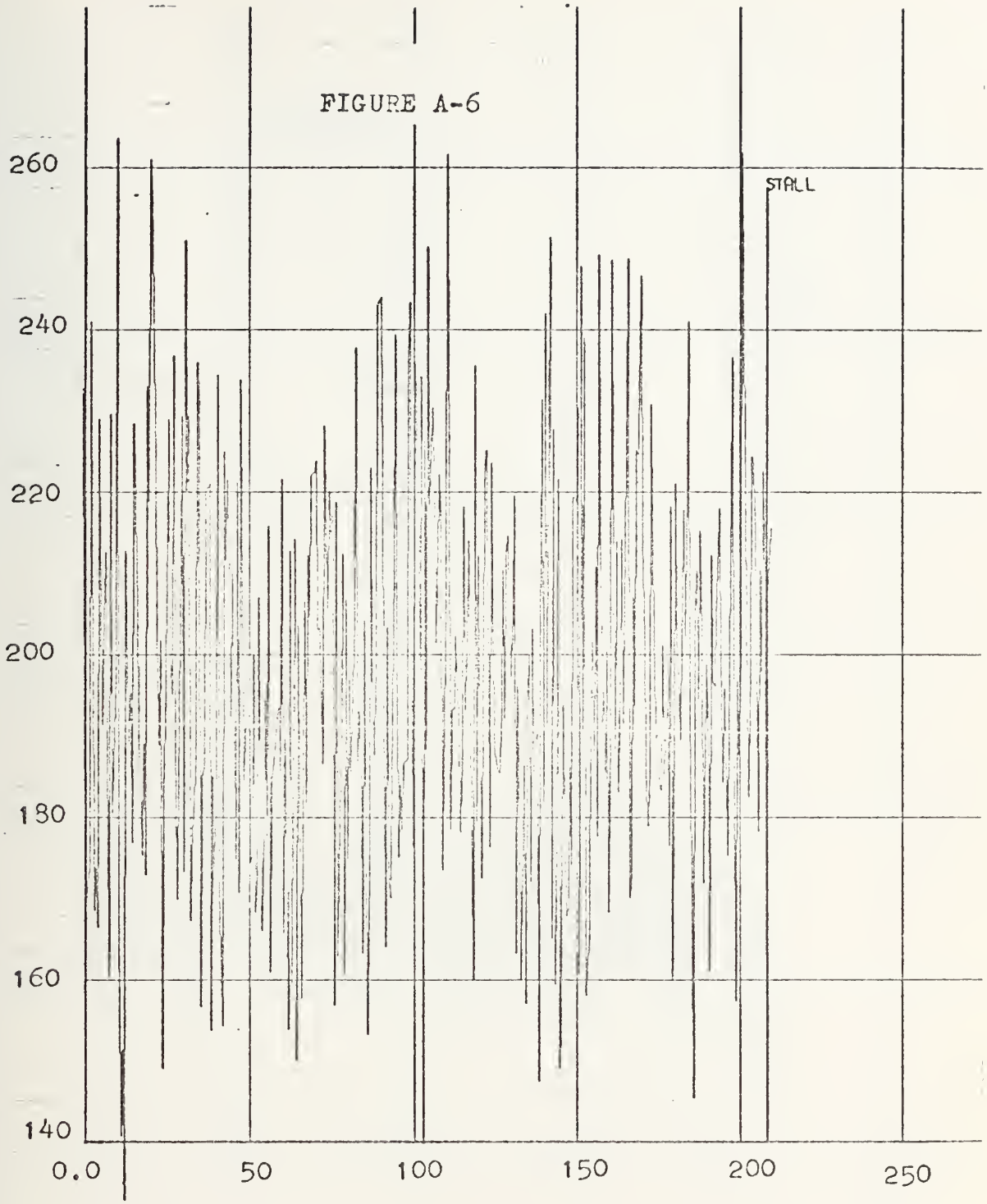


Downs Index

case two

index vs time in millisec

FIGURE A-6

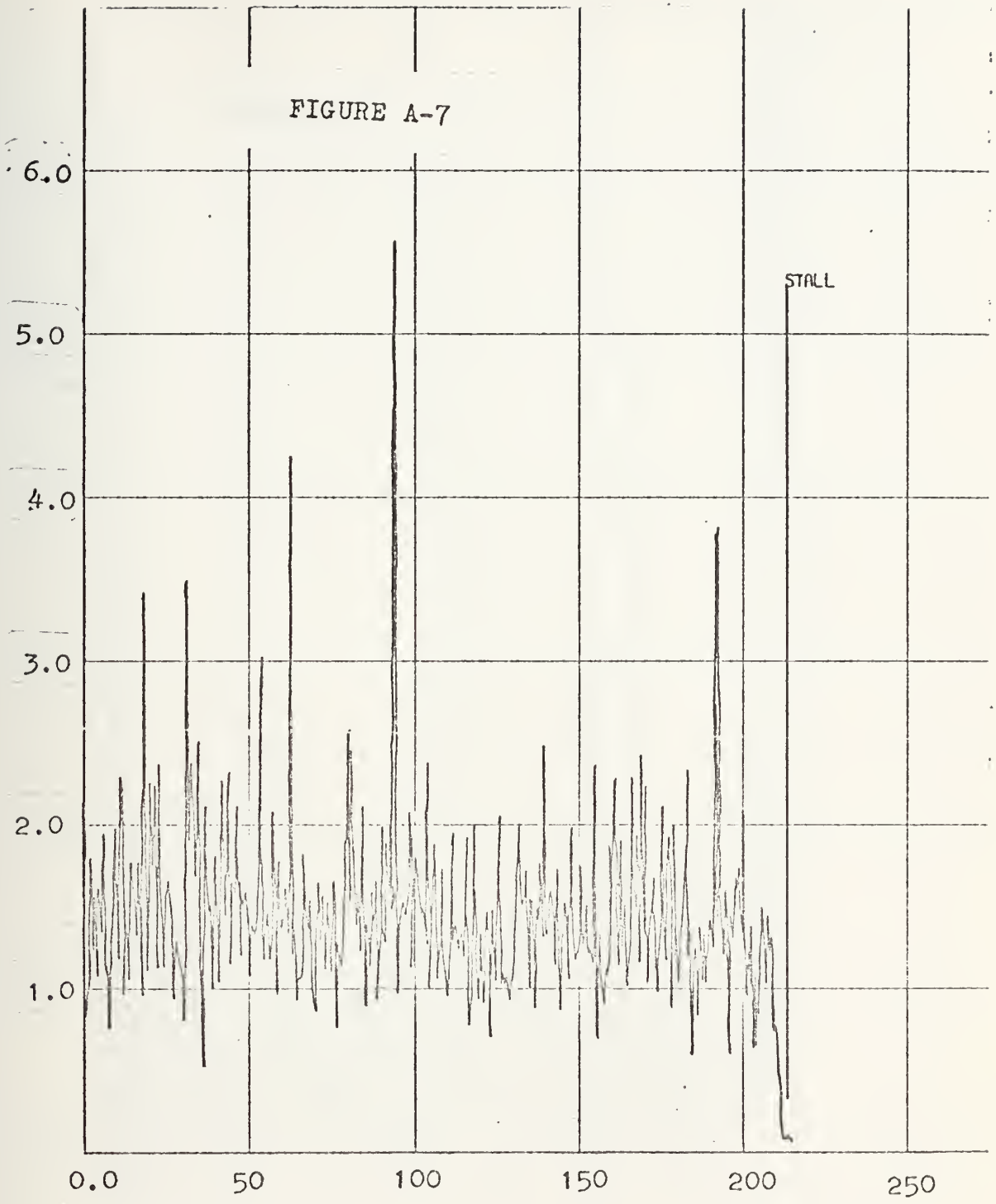


Pratt and Whitney Index

case two

index vs time in millisec

FIGURE A-7



Shoemaker Index

case three

index vs time in millisec

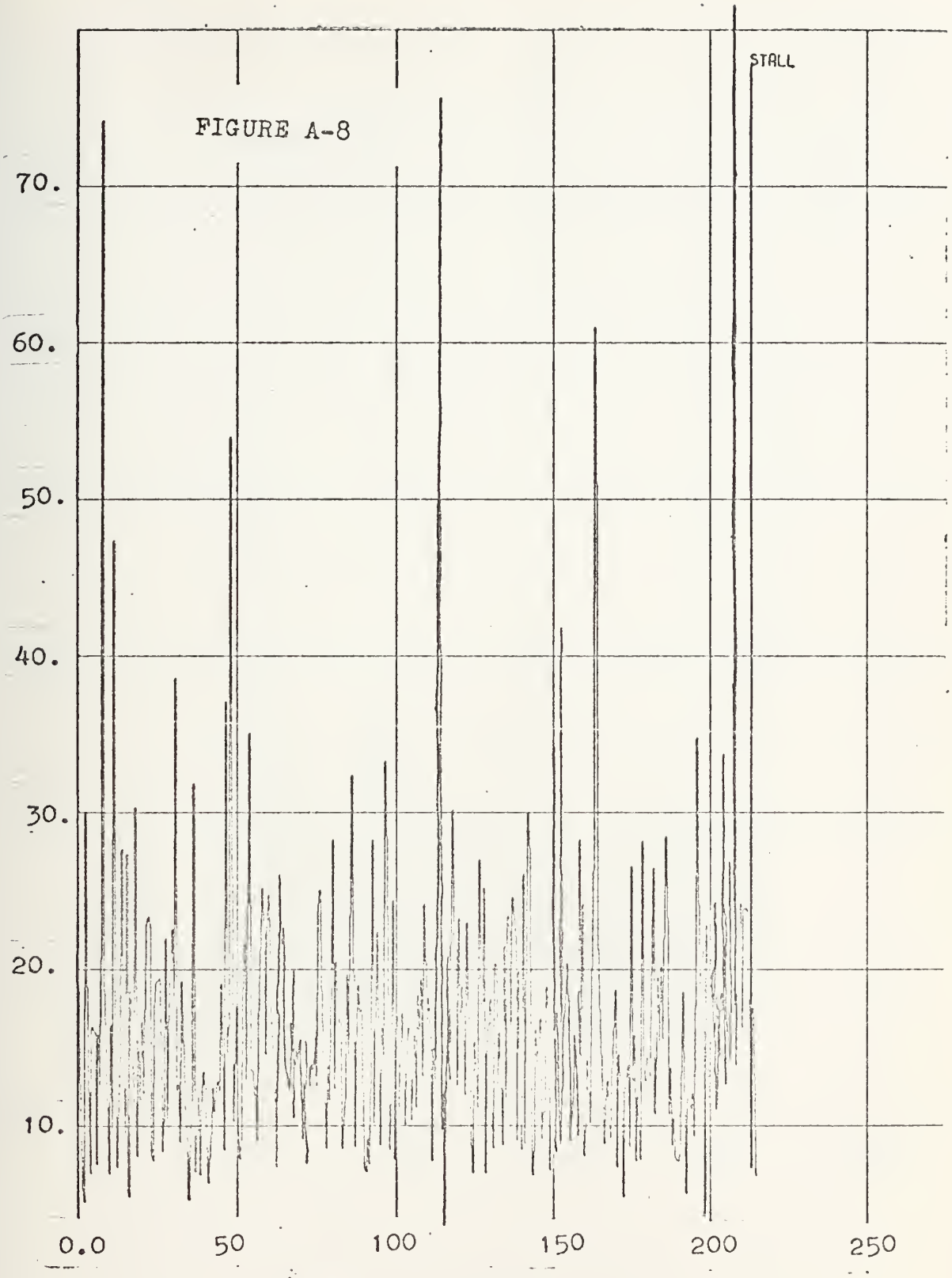
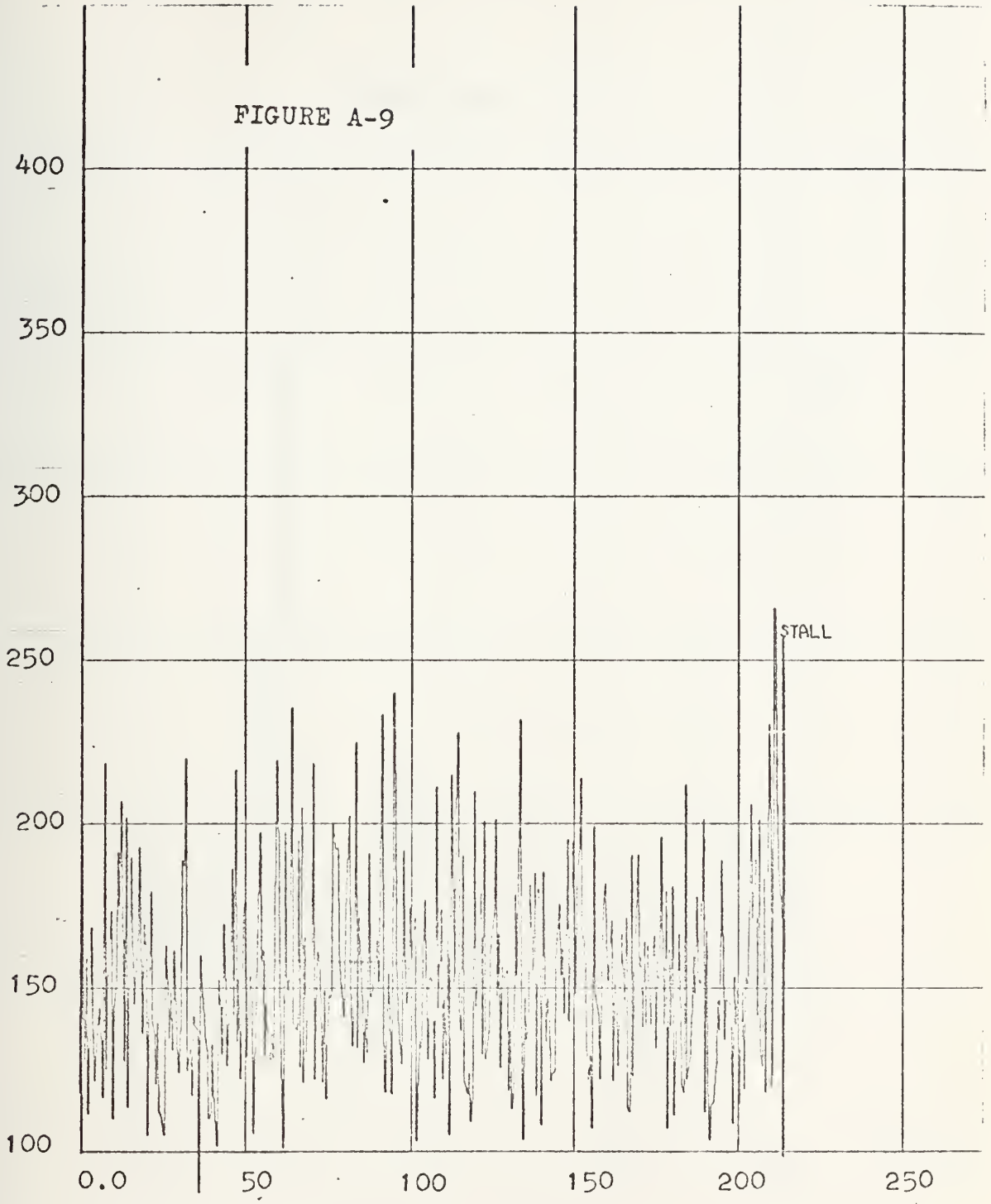


FIGURE A-8

Downs Index

case three

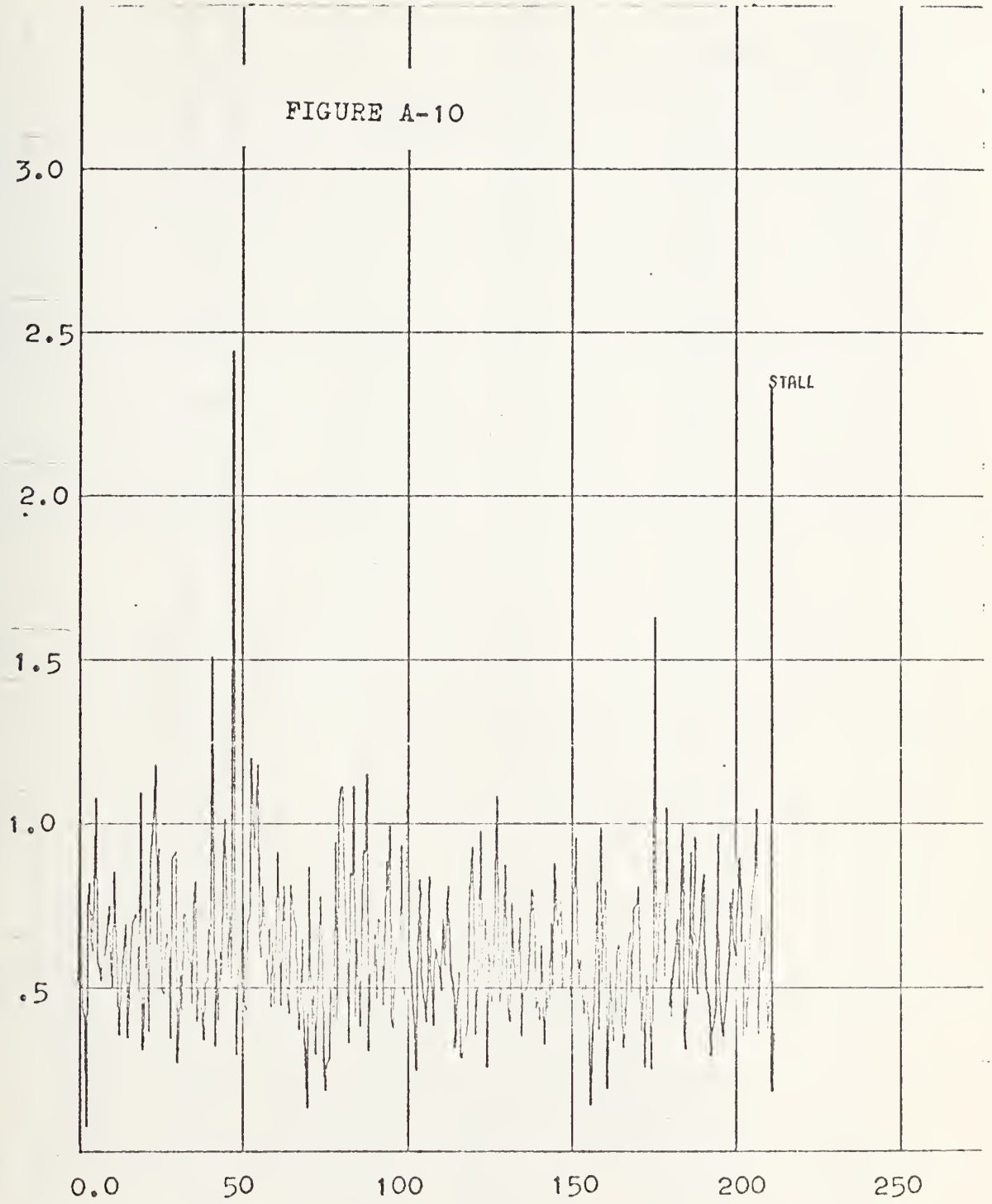
index vs time in millisec



Pratt and Whitney Index

case three

index vs time in millisec



Shoemaker Index

case four

index vs time in millisec

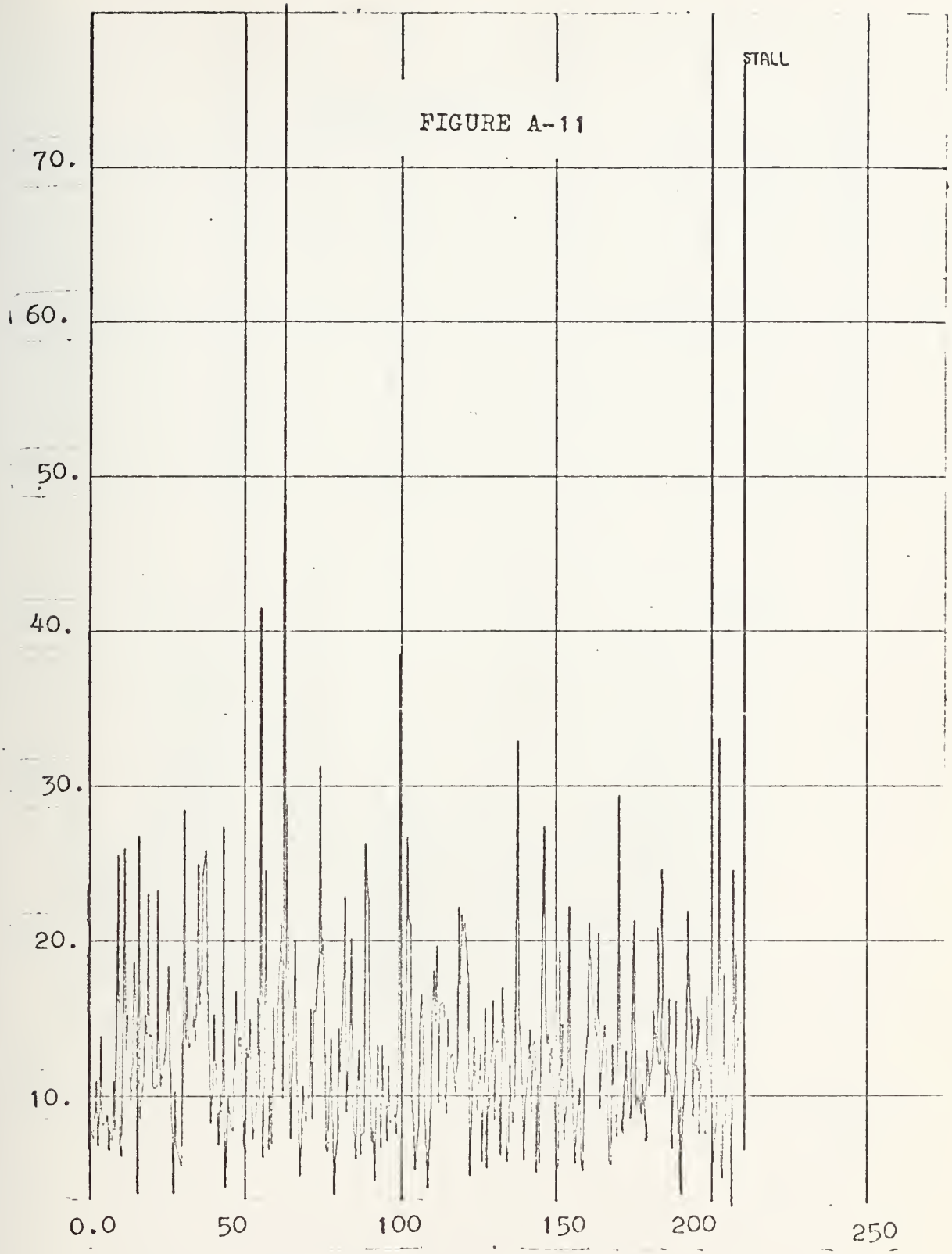
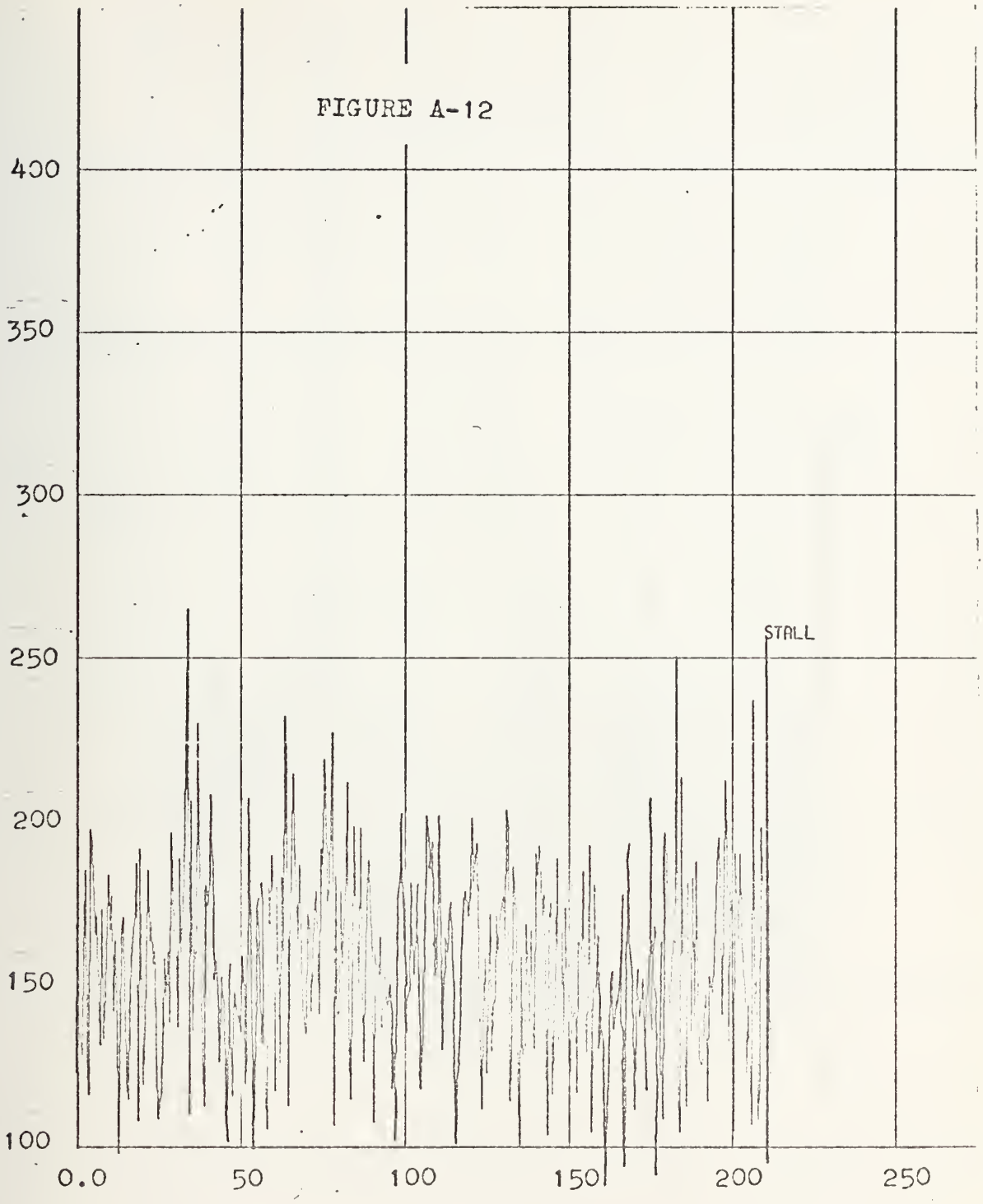


FIGURE A-11

Downs Index

case four

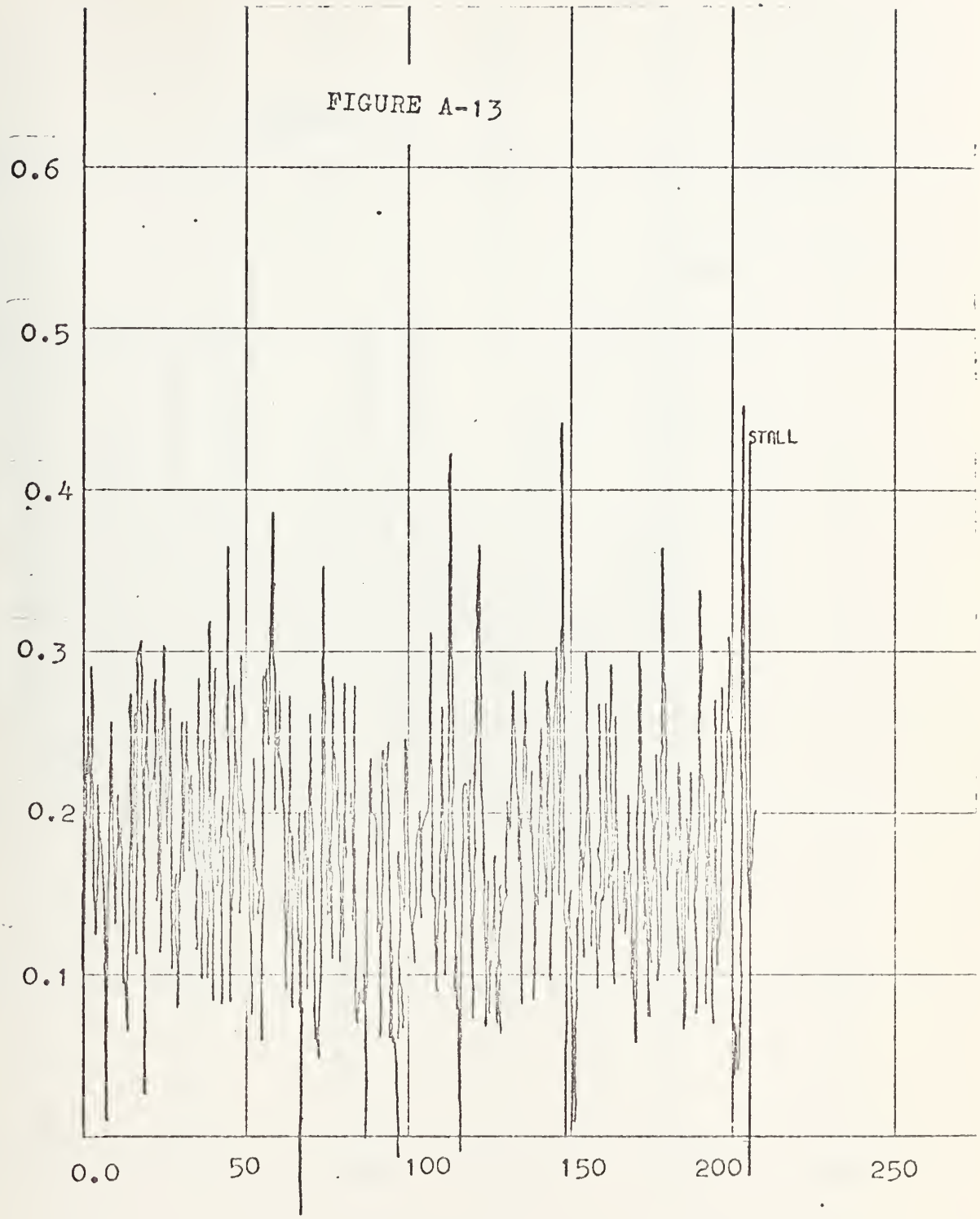
index vs time in millisec



Pratt and Whitney Index

case four

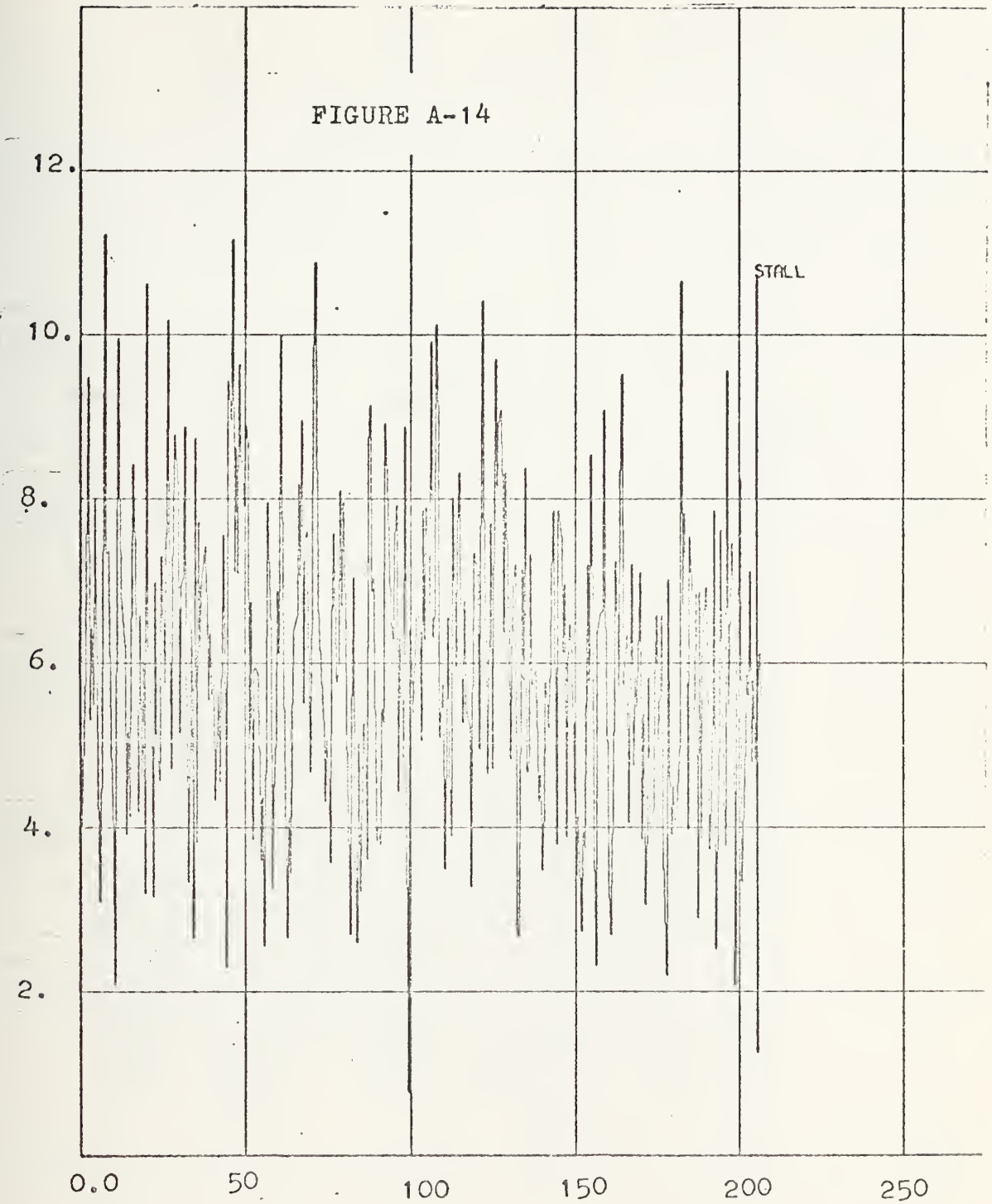
index vs time in millisec



Shoemaker Index

case five

index vs time in millisec

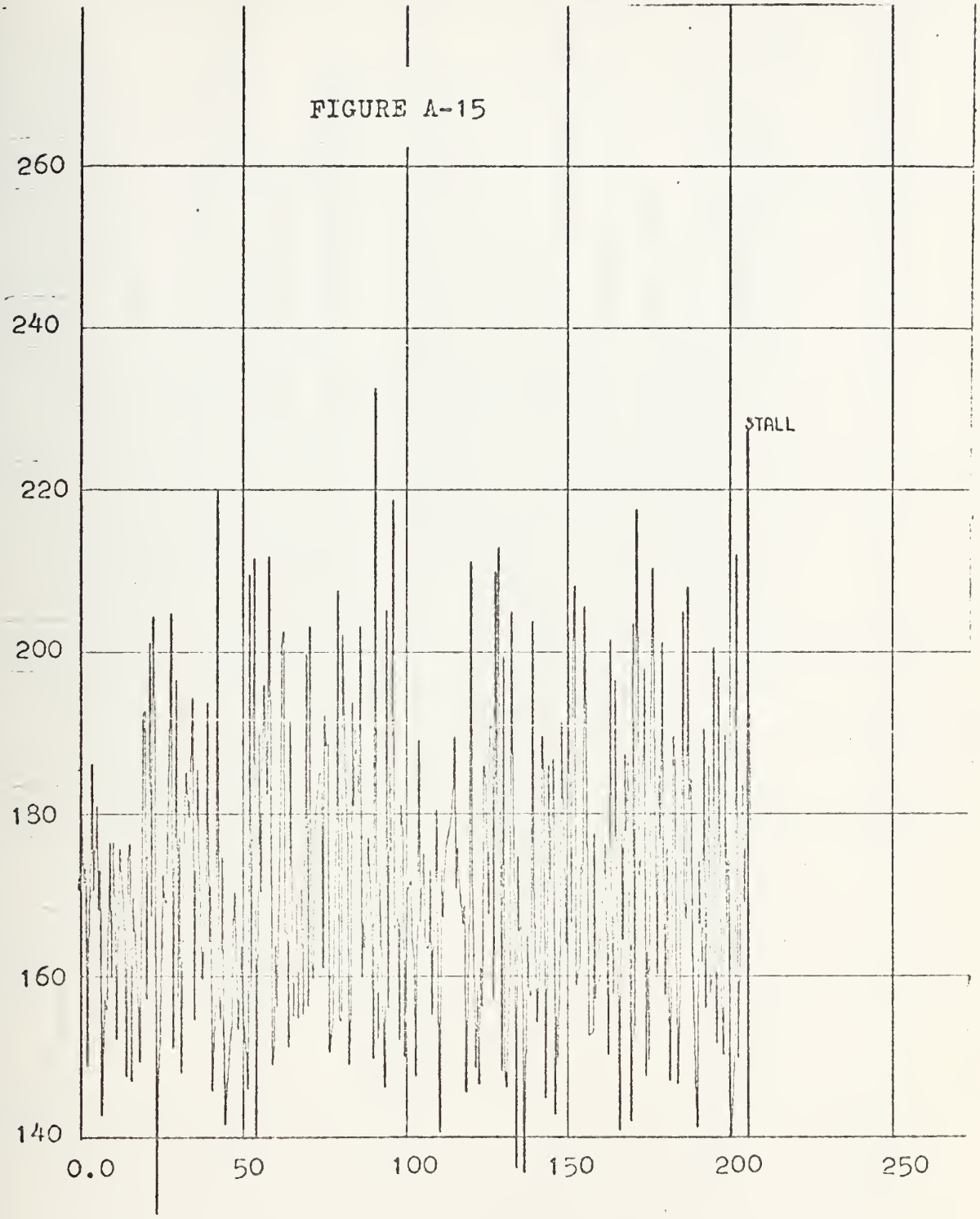


Downs Index

case five

index vs time in millisec

FIGURE A-15



Pratt and Whitney Index

case five

index vs time in millisec

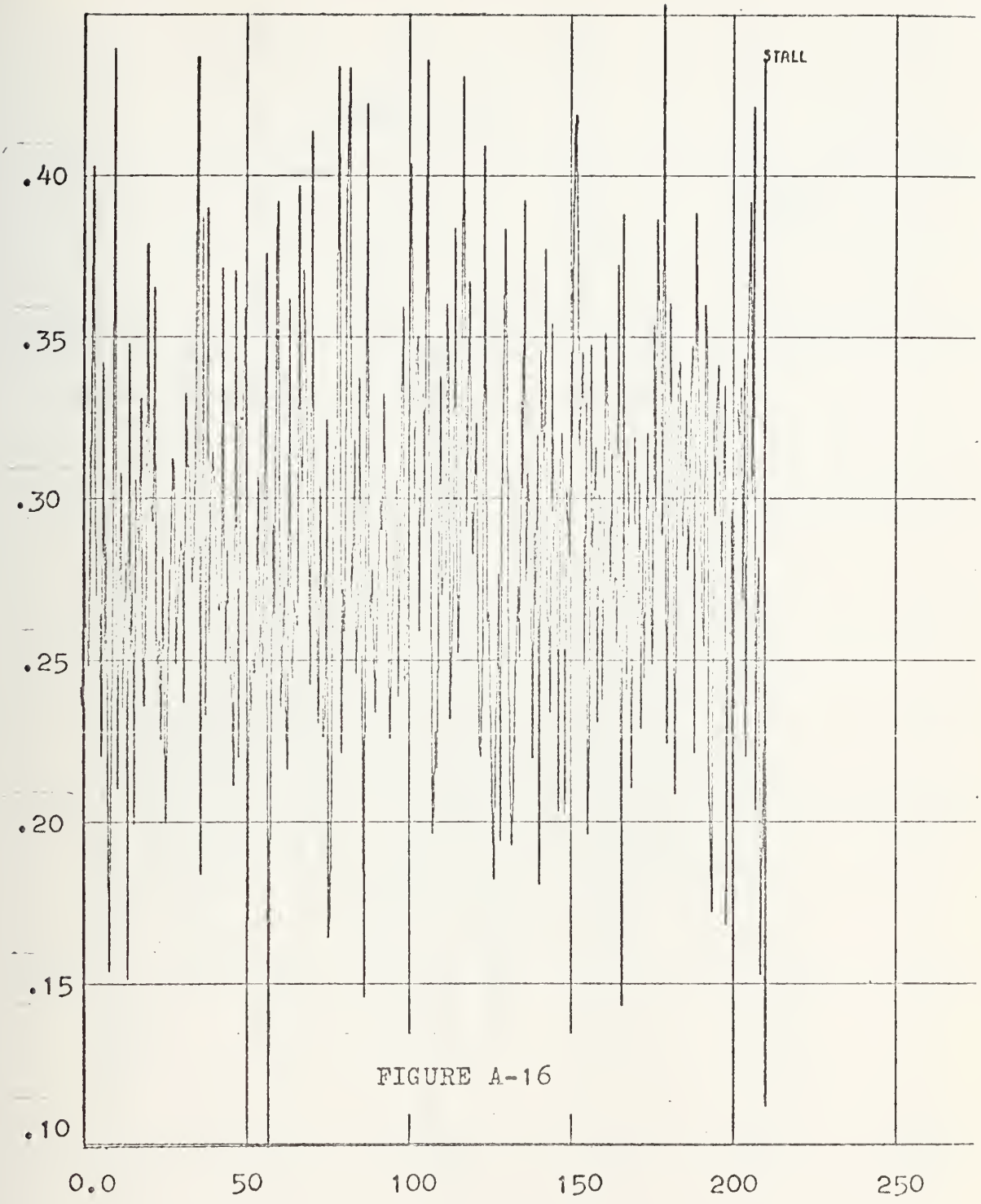
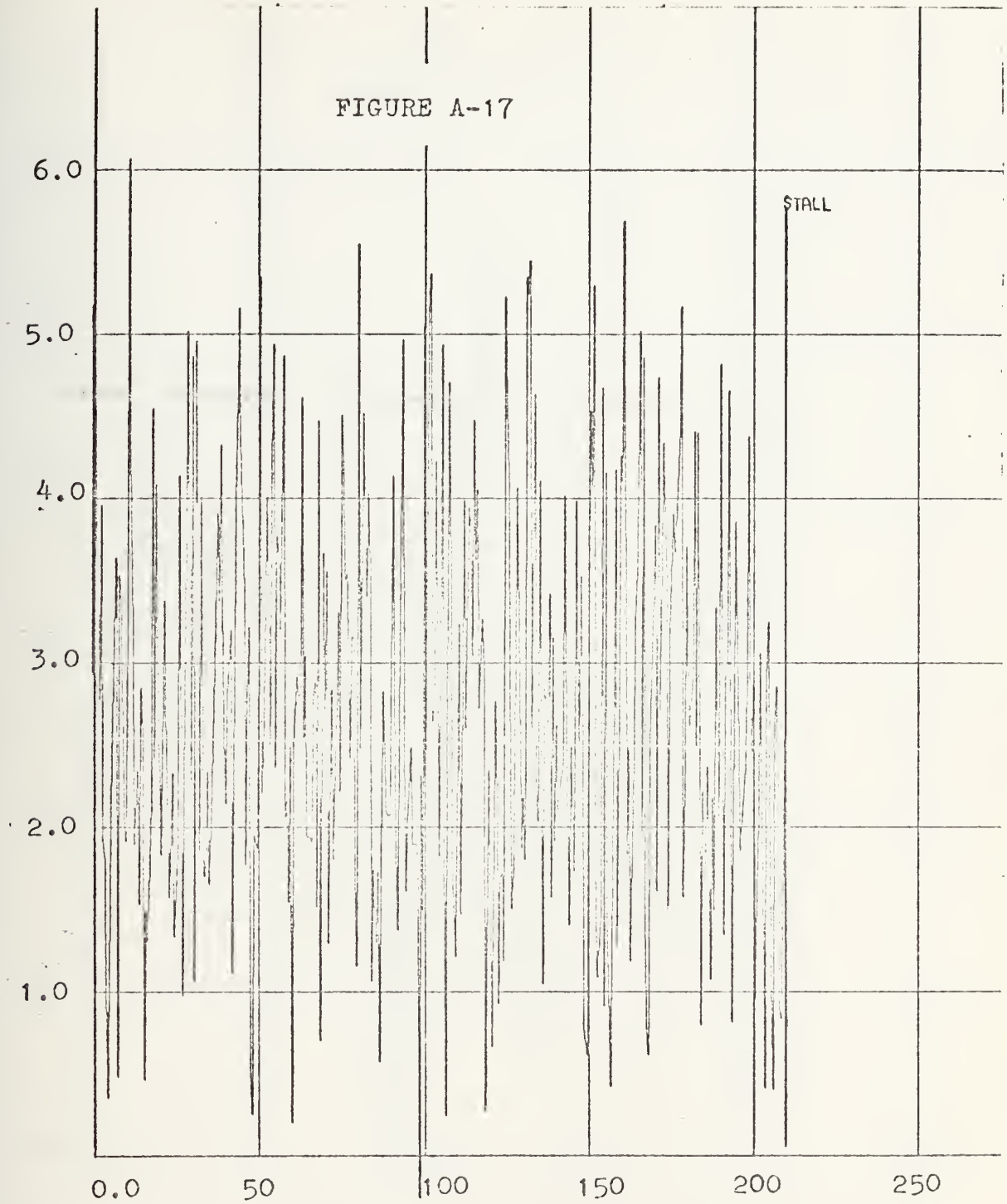


FIGURE A-16

Shoemaker Index

case six

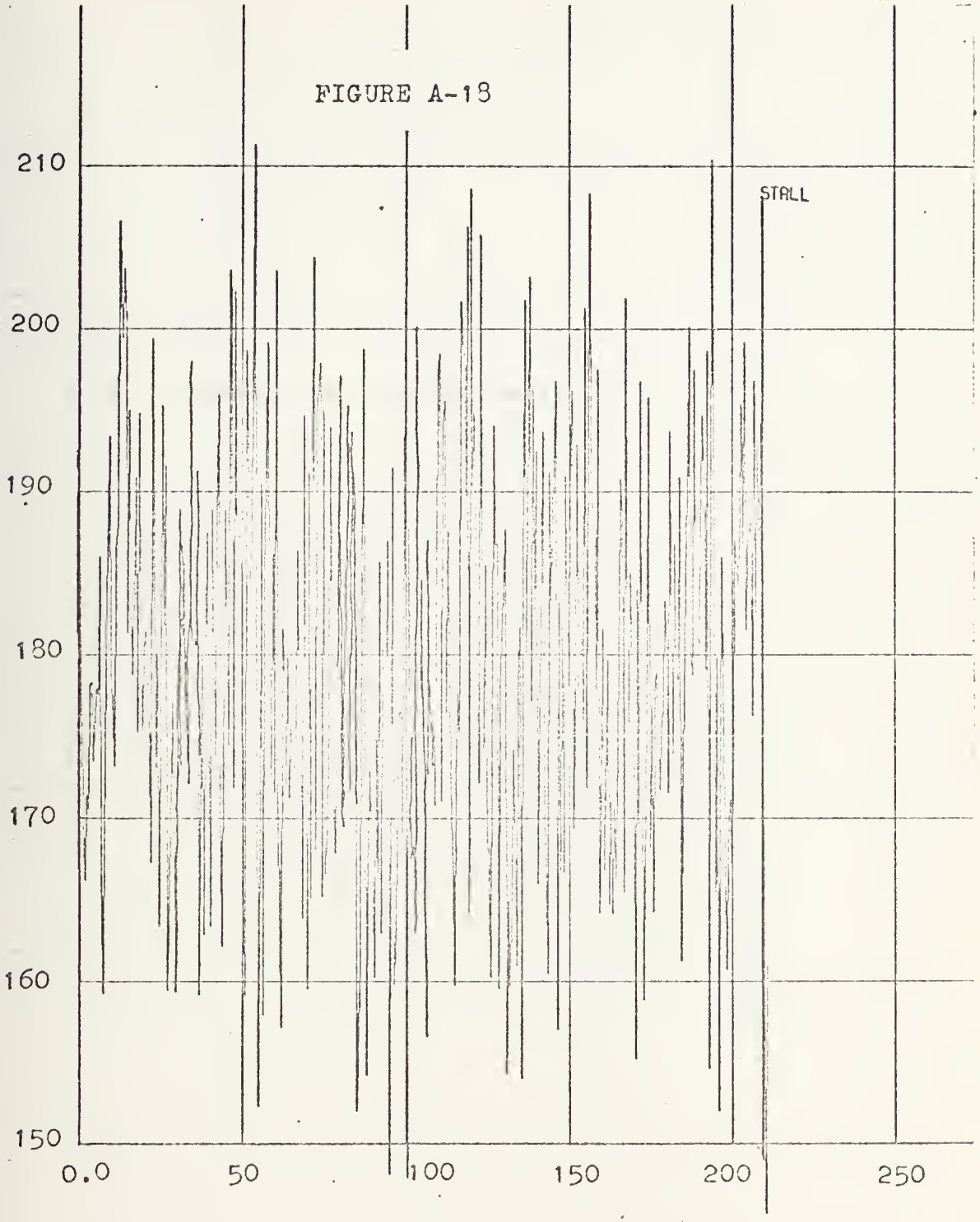
index vs time in millisec



Downs Index

case six

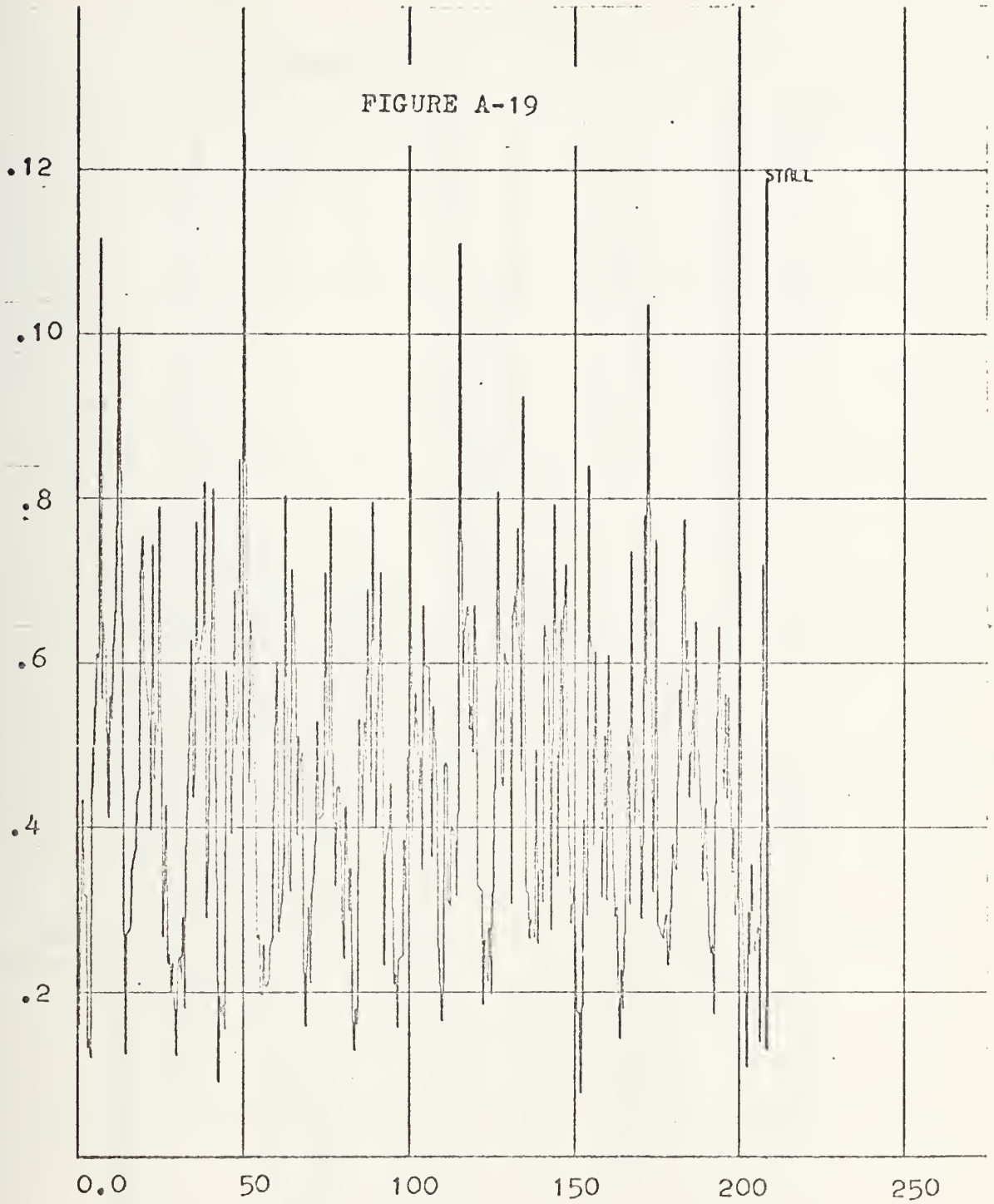
index vs time in millisec



Pratt and Whitney Index

case six

index vs time in millisec

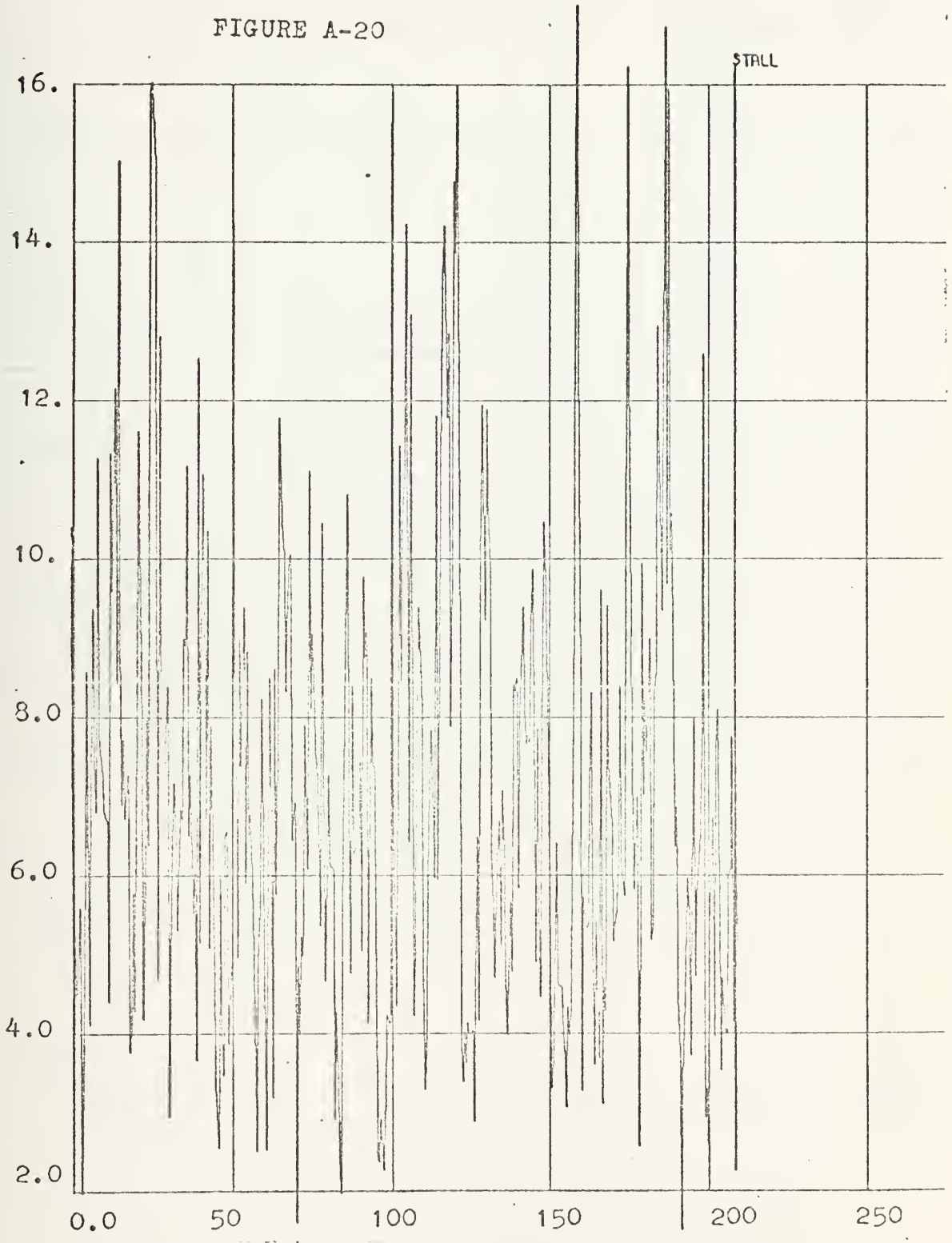


Shoemaker Index

case seven

index vs time in millisec

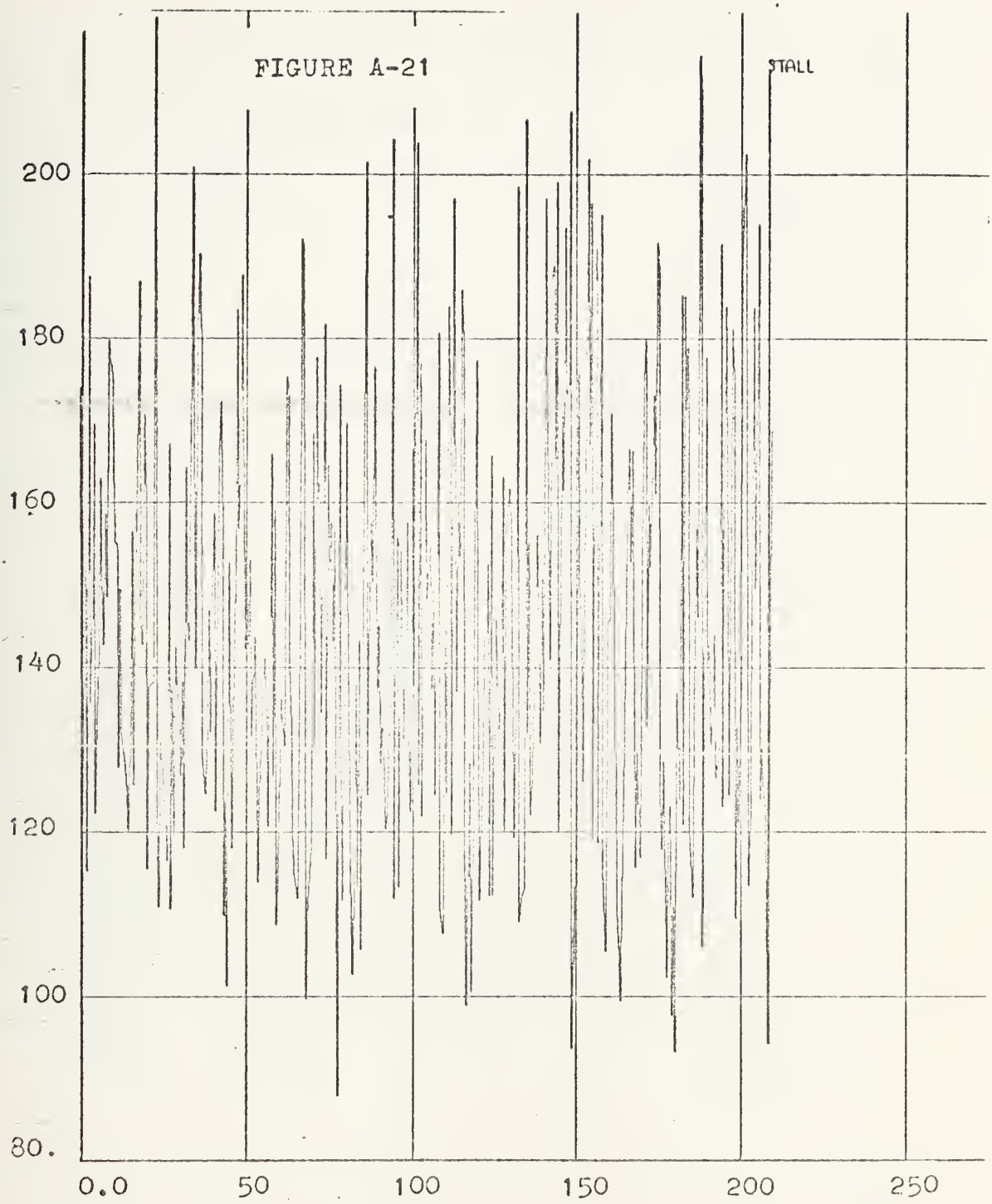
FIGURE A-20



Downs Index

case seven

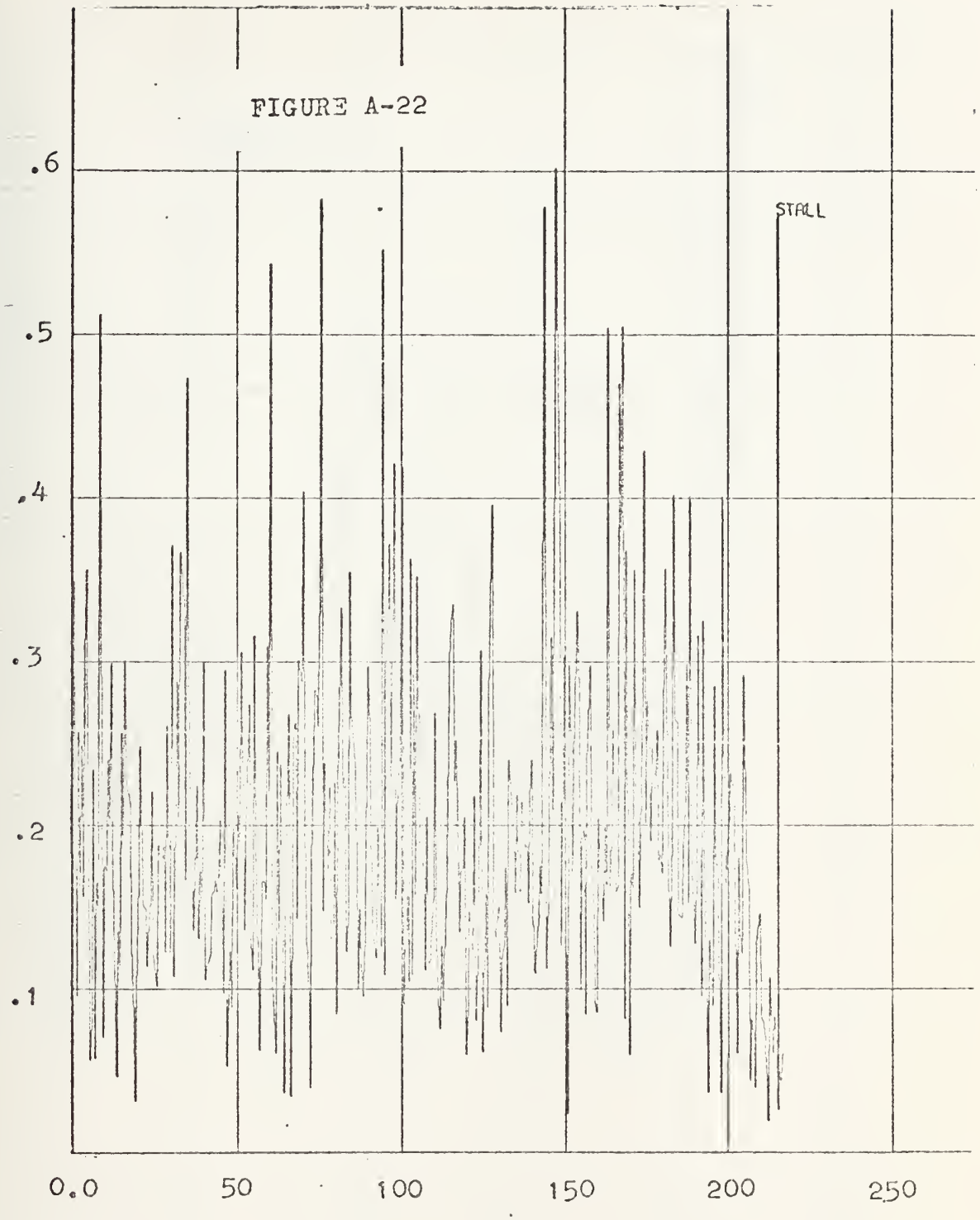
index vs time in millisec



Pratt and Whitney Index

case seven

index vs time in millisec



Shoemaker Index

case eight

index vs time in millisec

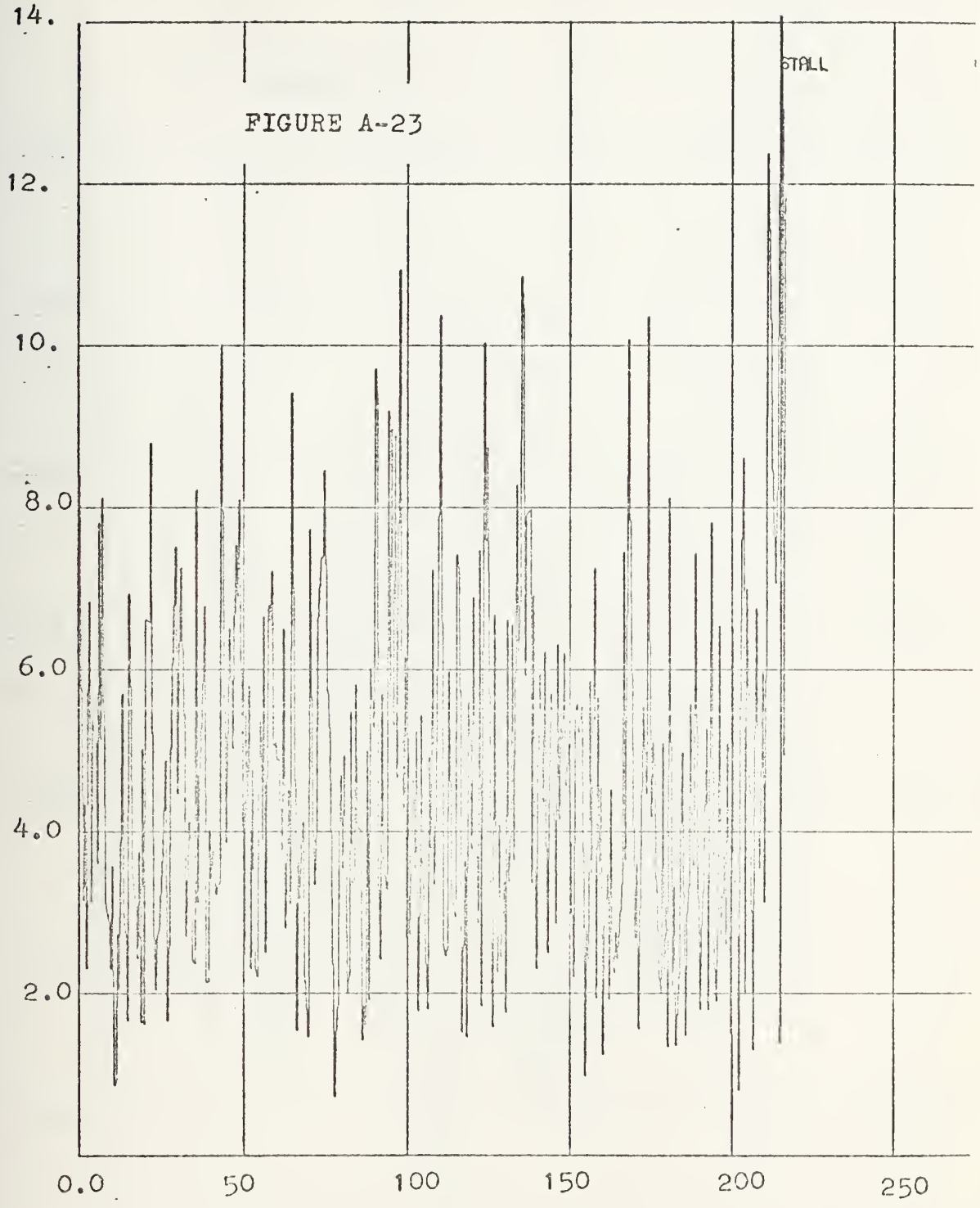
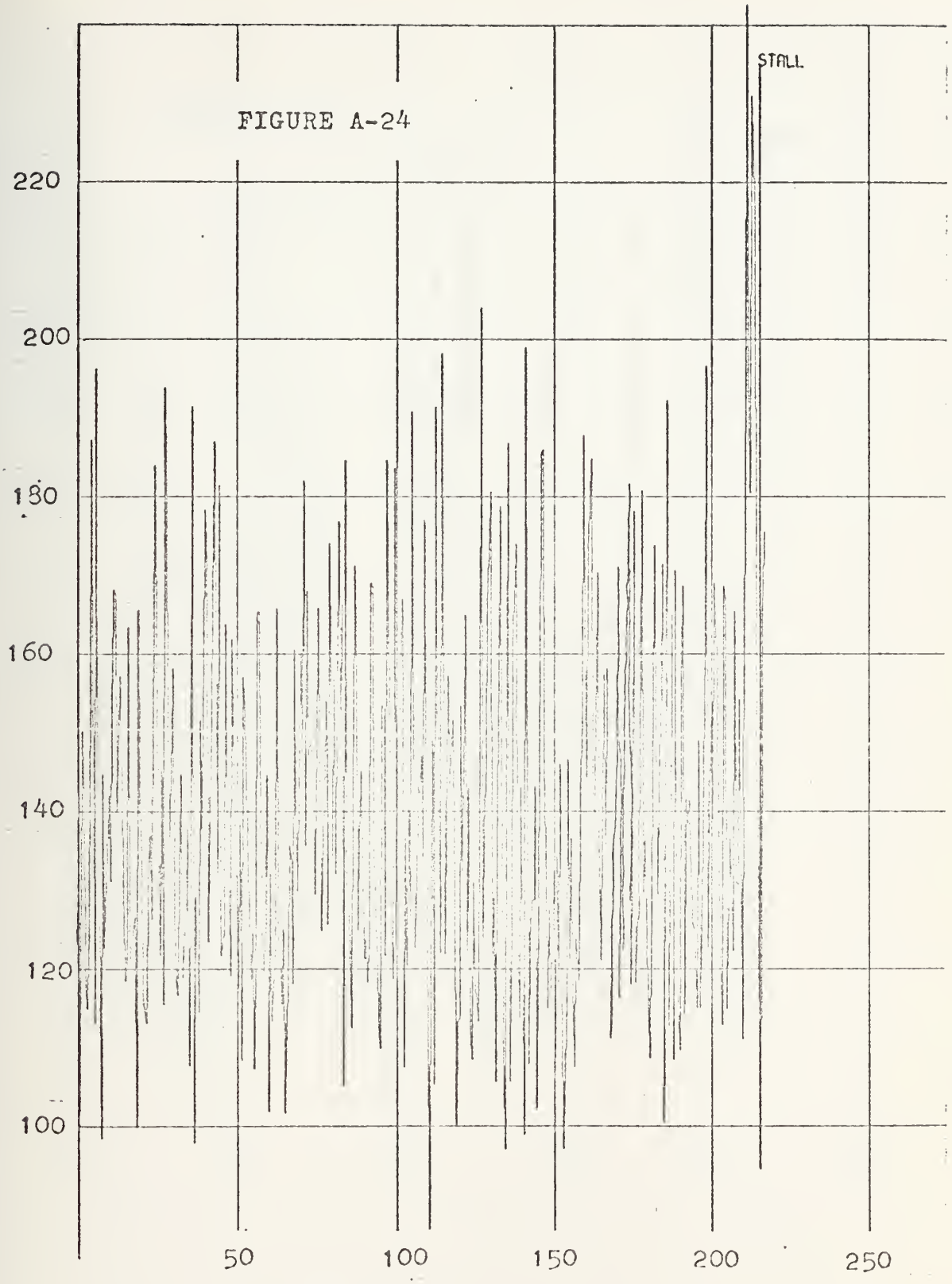


FIGURE A-23

Downs Index

case eight

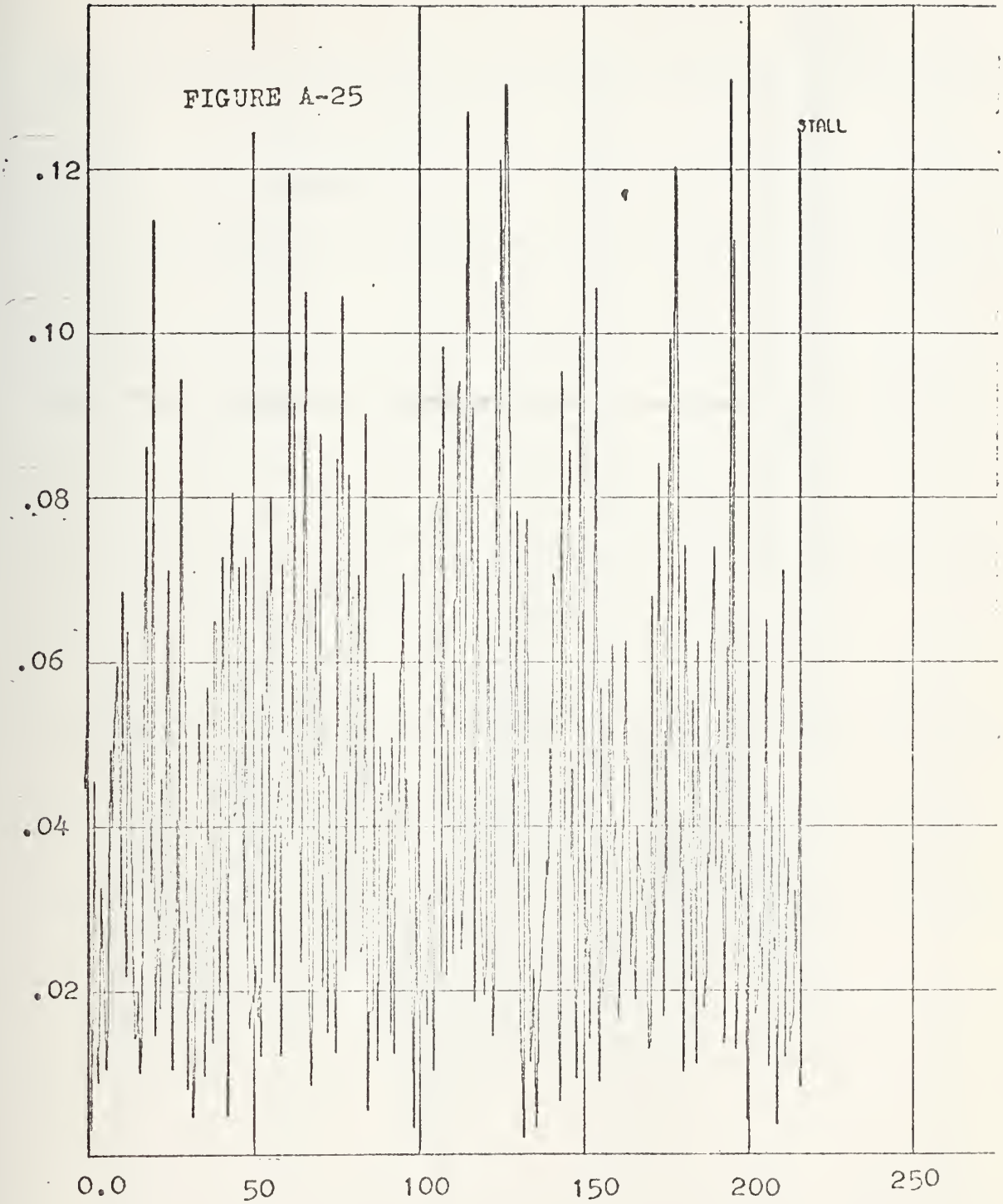
index vs time in millisec



Pratt and Whitney Index

case eight

index vs time in millisec



Shoemaker Index

case nine

index vs time in millisec

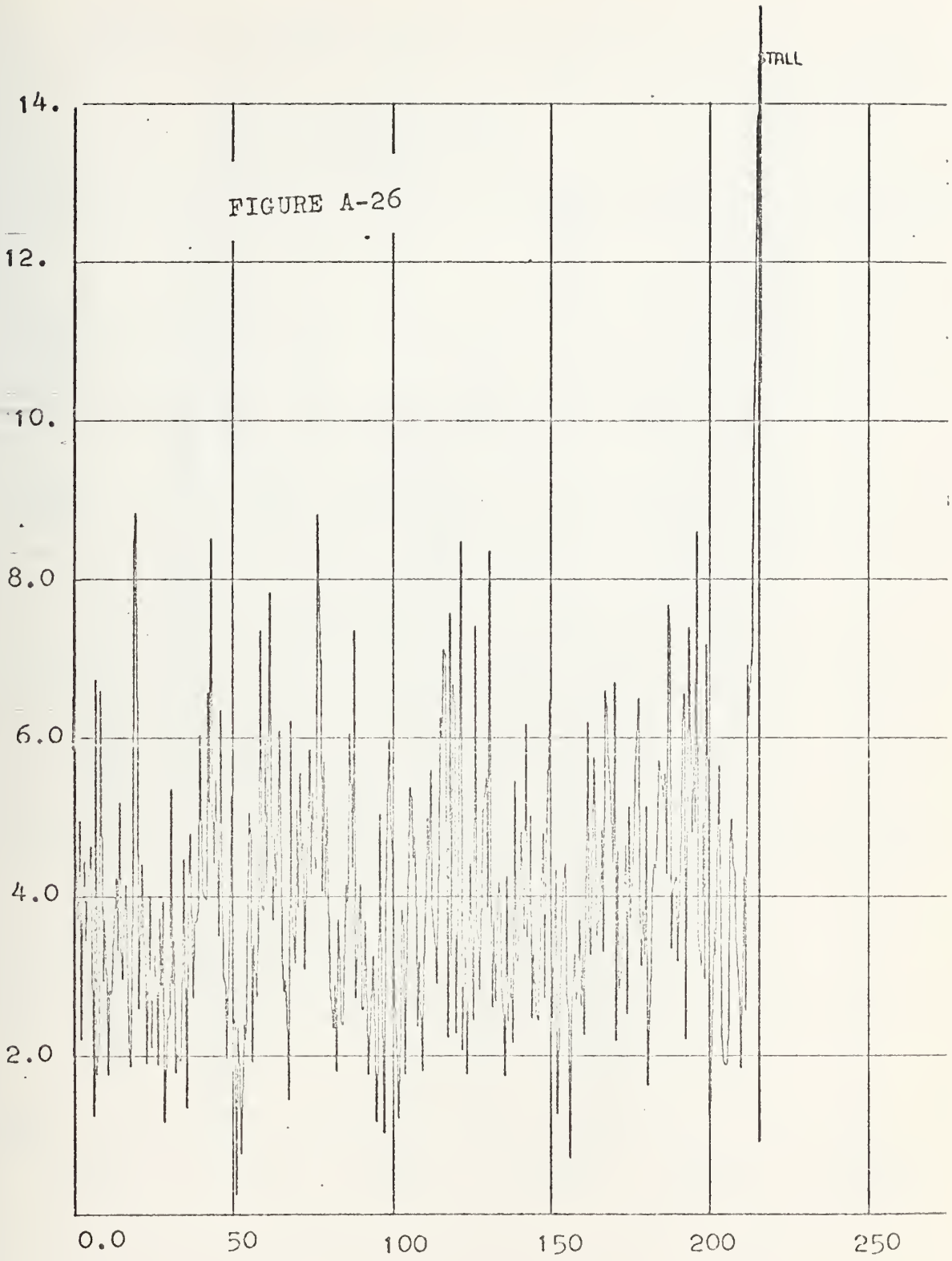
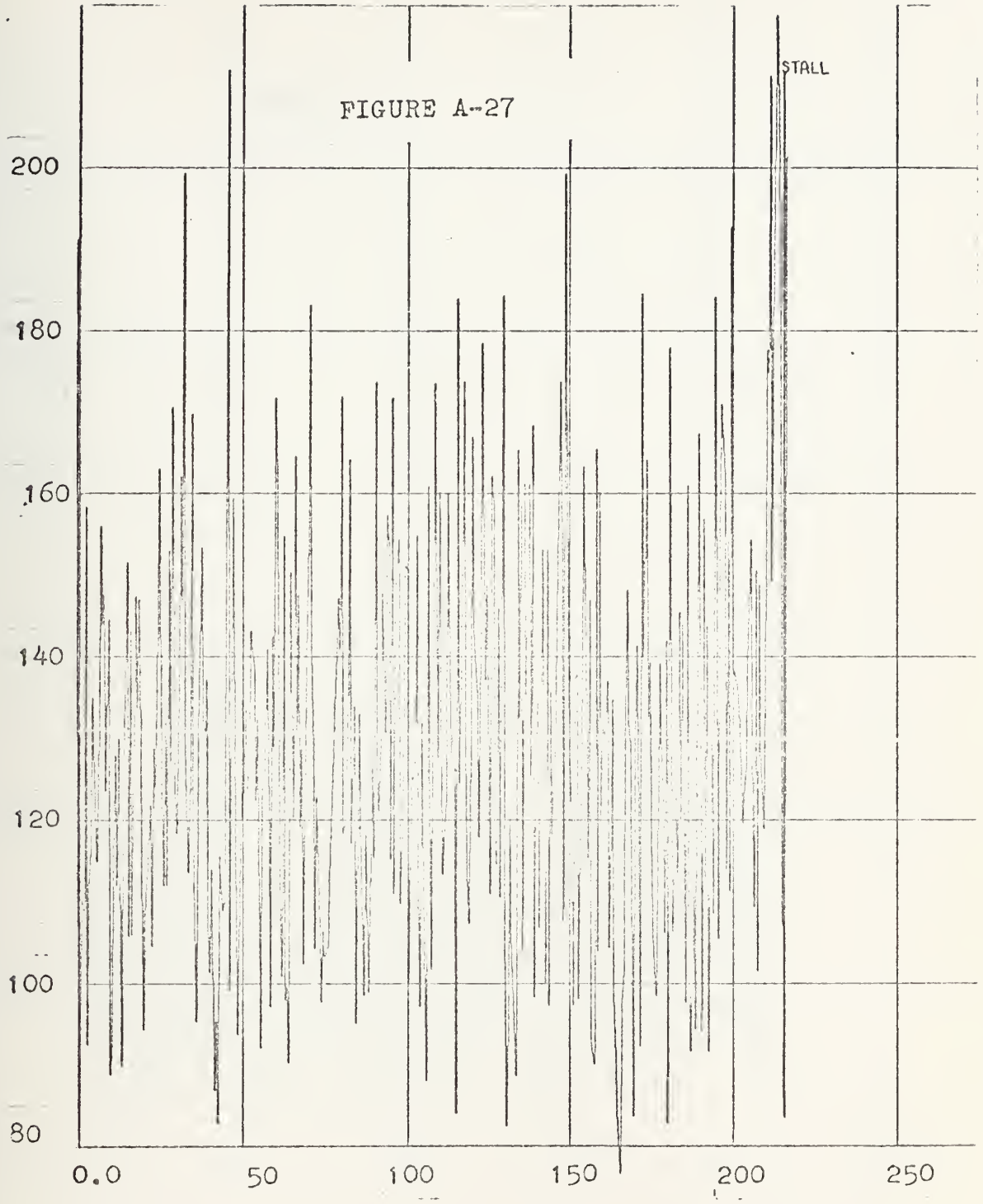


FIGURE A-26

Downs Index

case nine

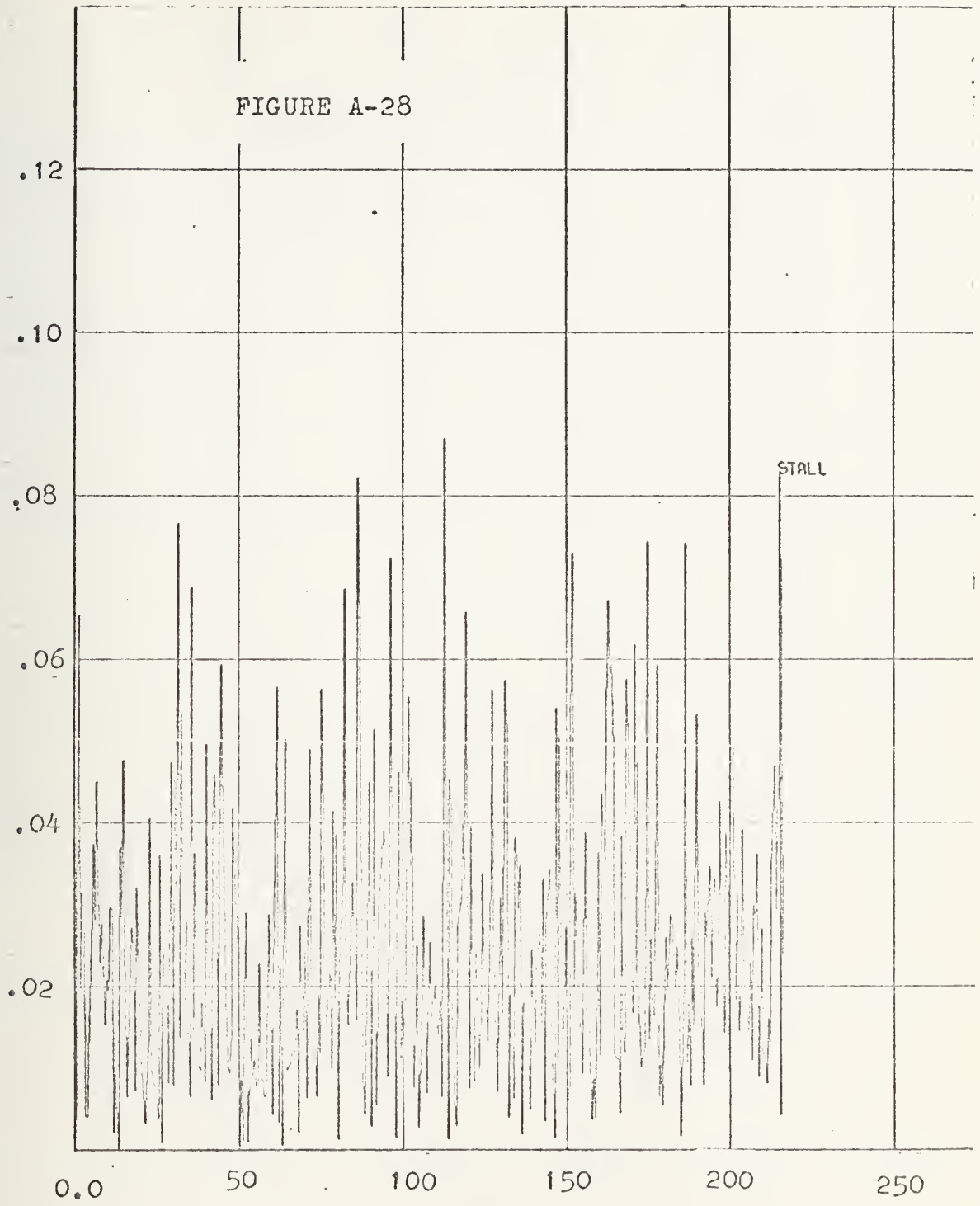
index vs time in millisec



Pratt and Whitney Index

case nine

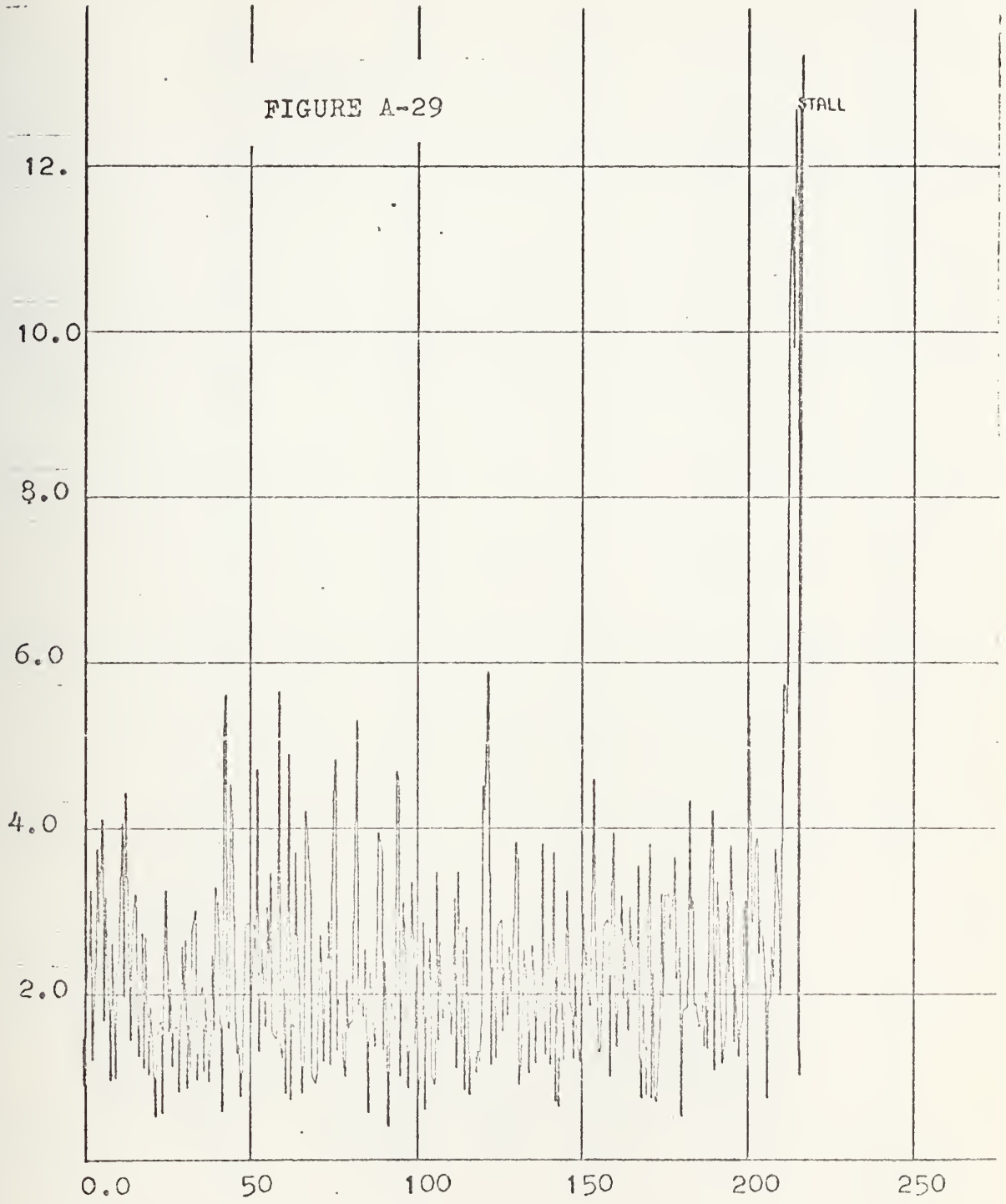
index vs time in millisec



Shoemaker Index

case ten

index vs time in millisec

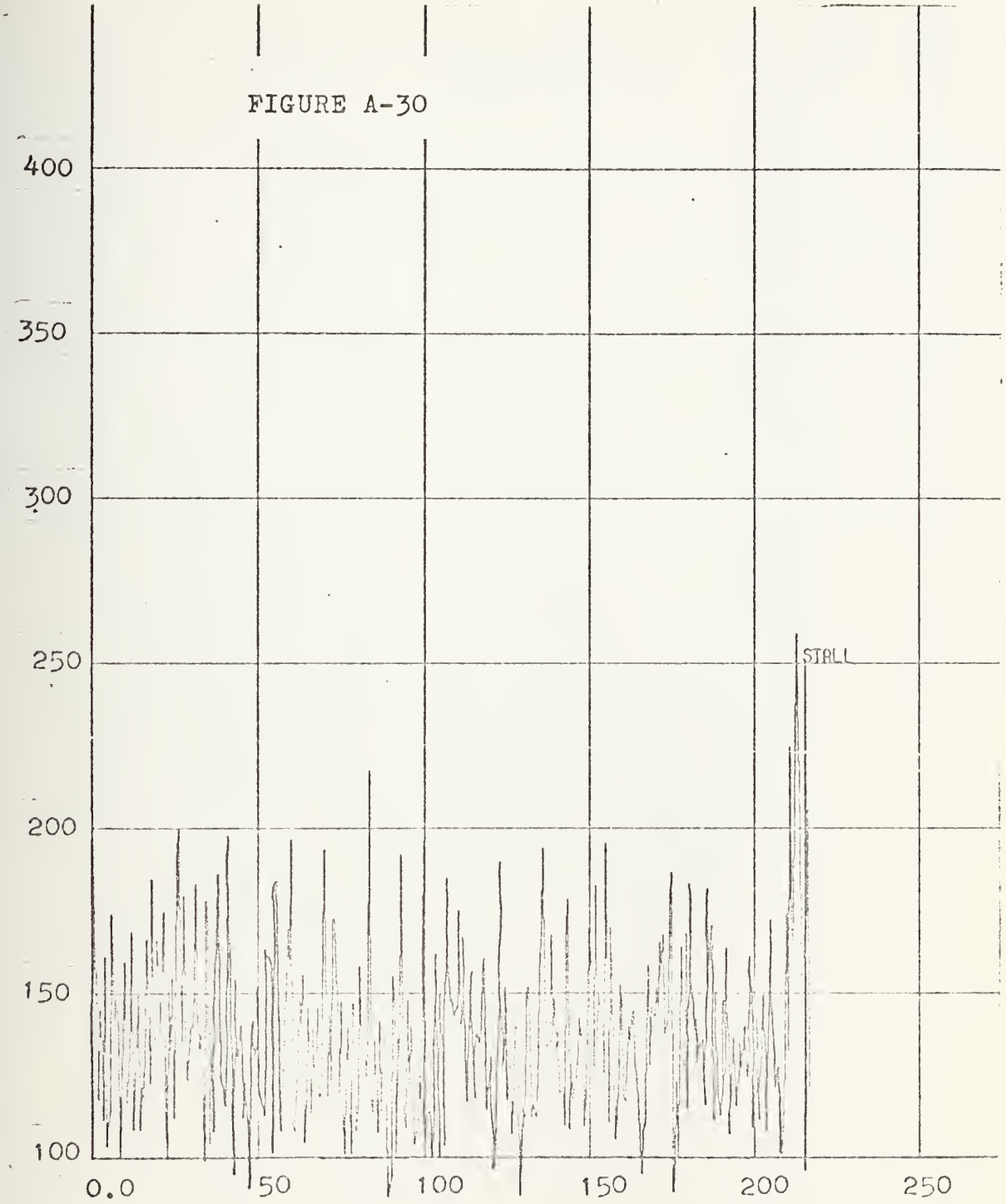


Downs Index

case ten

index vs time in millisec

FIGURE A-30

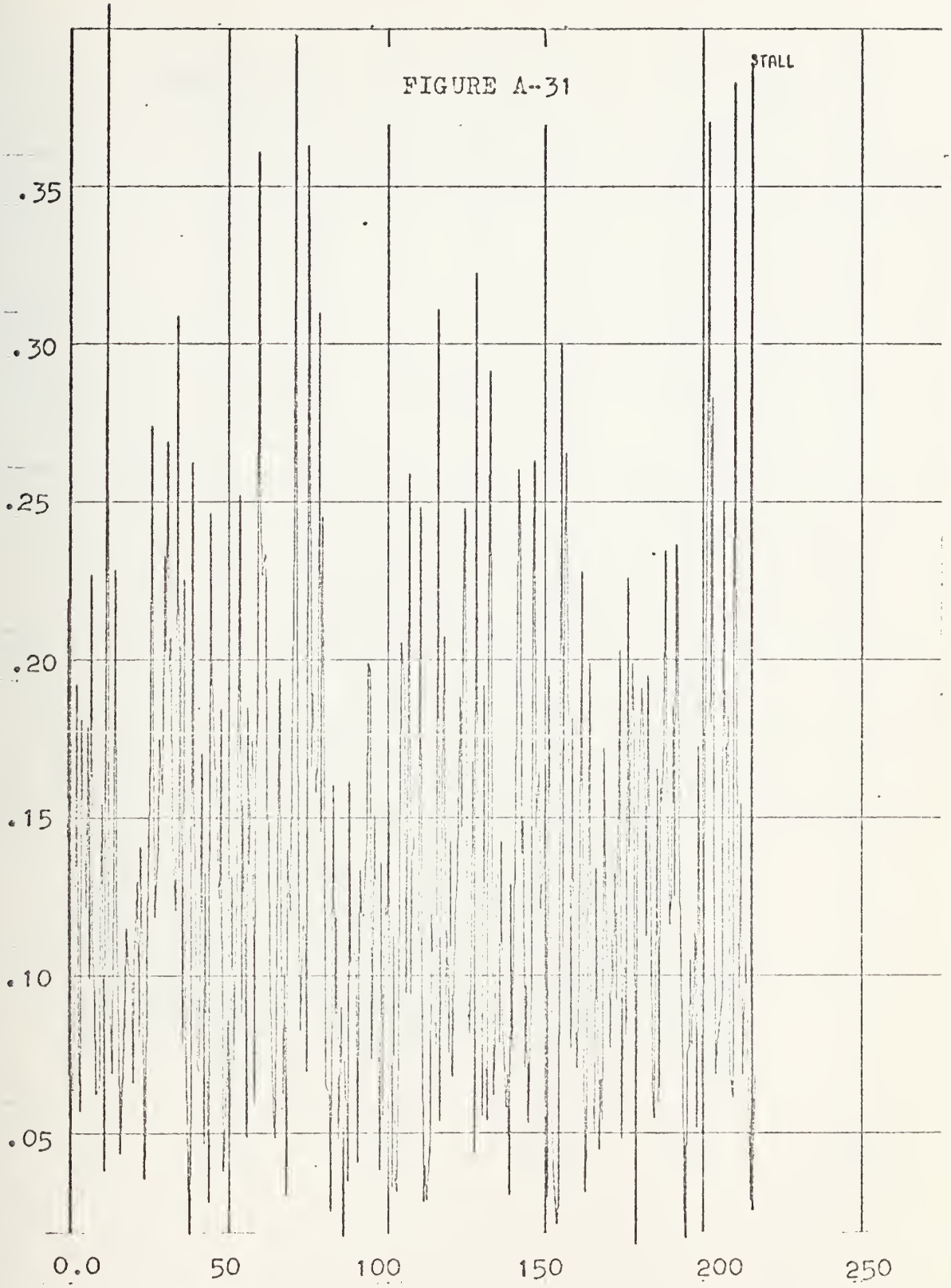


Pratt and Whitney Index

case ten

index vs time in millisec

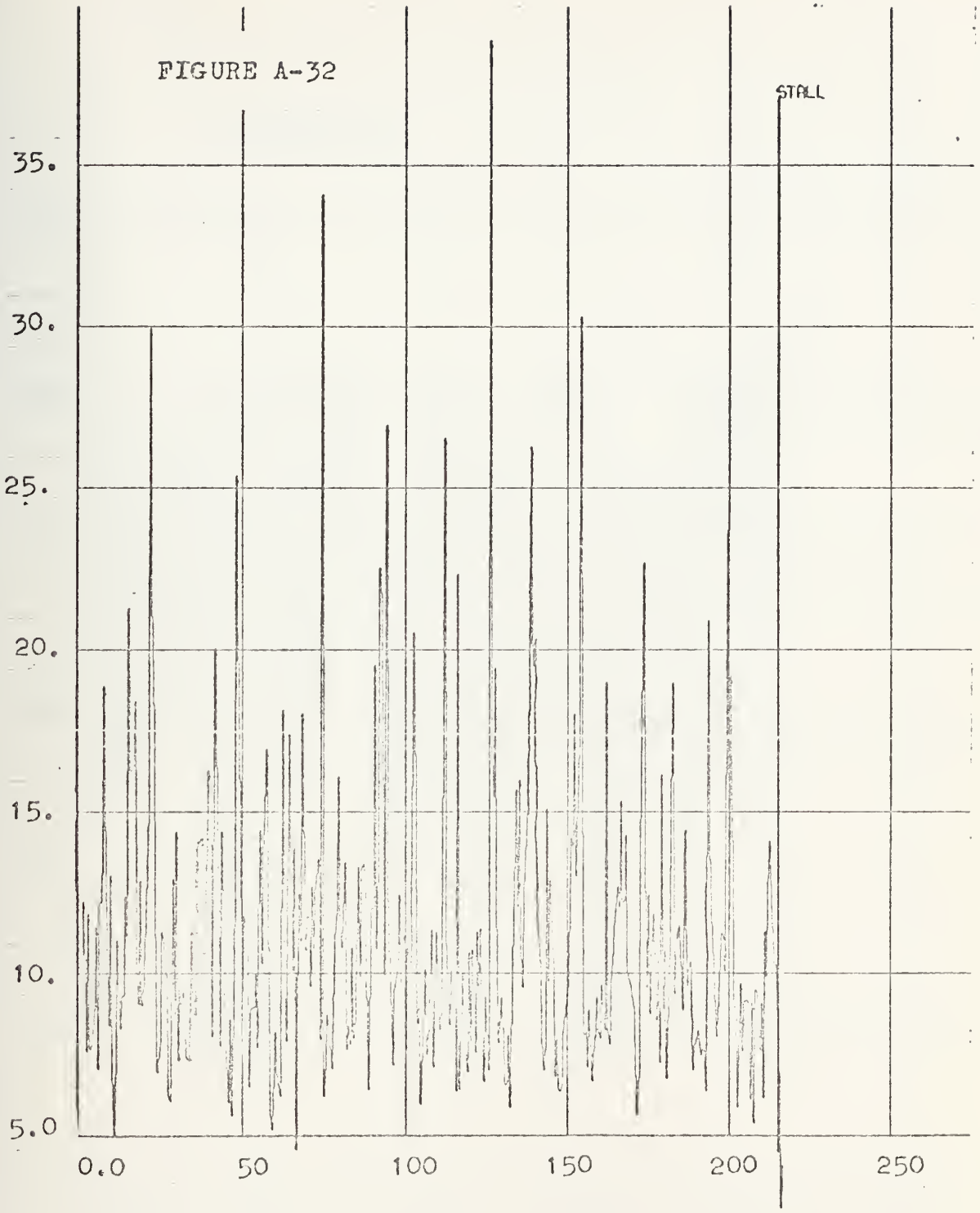
FIGURE A-31



Shoemaker Index

case eleven

index vs time in millisec

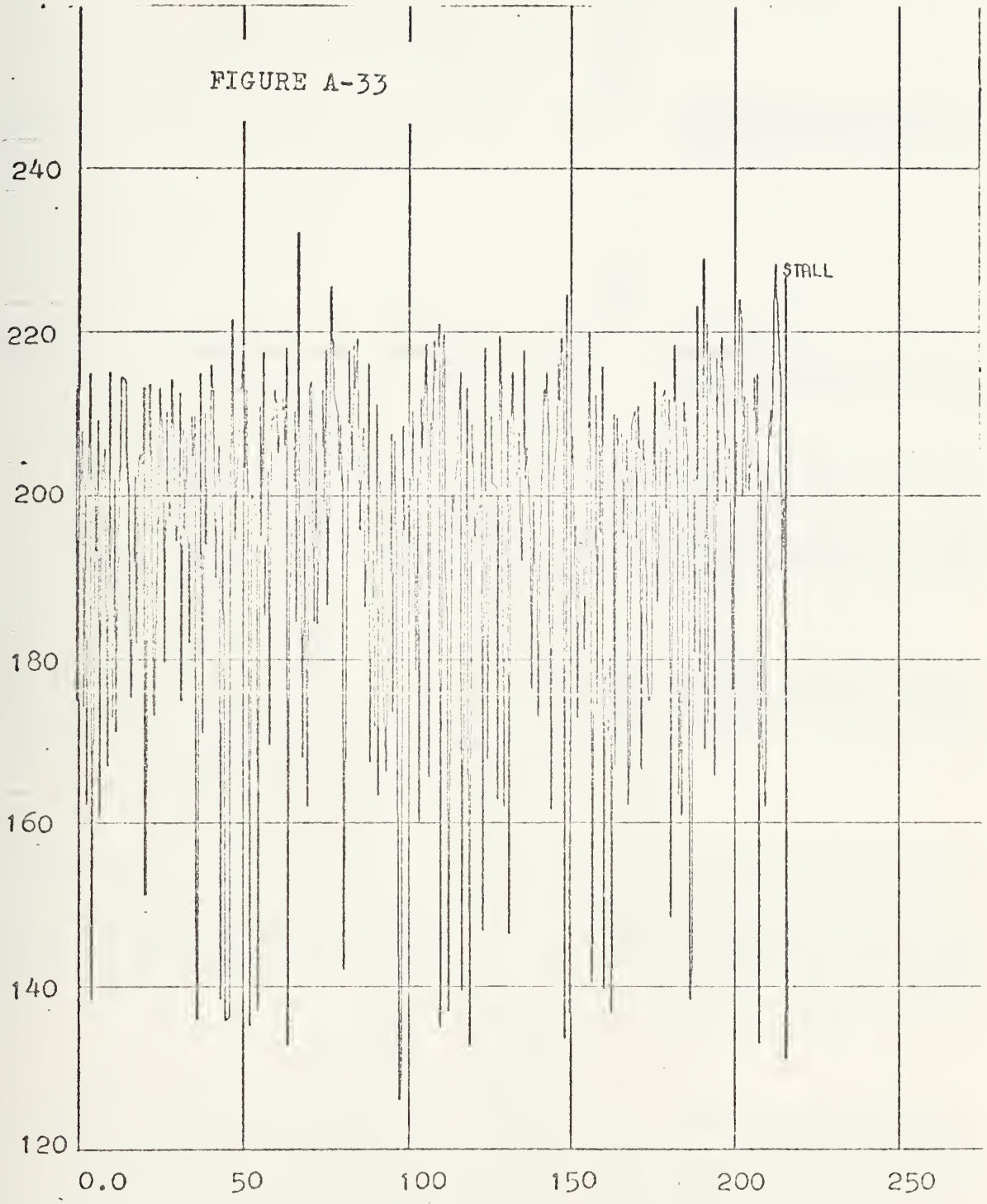


Downs Index

case eleven

index vs time in millisec

FIGURE A-33



Pratt and Whitney Index

case eleven

index vs time in millisec

SHUMAKER INDEX CASE 1

*** STALL WARNING *** TIME IS 122.625
*** STALL WARNING *** TIME IS 123.250
*** STALL WARNING *** TIME IS 123.875

False Warning

*** STALL WARNING *** TIME IS 180.125
*** STALL WARNING *** TIME IS 180.750
*** STALL WARNING *** TIME IS 181.375

Stall Prediction

STALL CCCURRED AT TIME 202.40

CASE NUMBER 1
AVERAGE STATIC PRESSURE IS 1328.400

TAPE WAS READ 52 TIMES

N	DFACT(N)	FACT(N)	TIME	PTAVE	MEAN	STD-DEV
1	0.12355E 01	0.12355E 01	0.125	1627.196	0.0	0.0
2	0.13216E 01	0.13216E 01	0.750	1562.030	0.0	0.0
3	0.12916E 01	0.12916E 01	1.375	1538.681	0.0	0.0
4	0.74304E 00	0.74304E 00	2.000	1557.724	0.0	0.0
5	0.12172E 01	0.12172E 01	2.625	1584.998	0.0	0.0
6	0.12167E 01	0.12167E 01	3.250	1578.427	0.0	0.0
7	0.12919E 01	0.12919E 01	3.875	1485.197	0.0	0.0
8	0.49211E 00	0.49211E 00	4.125	1518.660	0.0	0.0
9	0.68846E 00	0.68846E 00	4.750	1543.234	0.0	0.0
10	0.52506E 00	0.52506E 00	5.375	1571.415	0.0	0.0
11	0.74898E 00	0.74898E 00	6.000	1607.881	0.0	0.0
12	0.10455E 01	0.10455E 01	6.625	1579.056	0.0	0.0
13	0.95914E 00	0.95914E 00	7.250	1586.720	0.0	0.0
14	0.98429E 00	0.98429E 00	7.875	1577.566	0.0	0.0
15	0.96495E 00	0.96495E 00	8.125	1578.567	0.0	0.0

112	0.92612E 00	0.13063E 01	63.875	1576.907	0.0	0.0
113	0.10741E 01	0.12415E 01	64.125	1576.356	0.0	0.0
114	0.10967E 01	0.74235E 00	64.750	1546.616	0.0	0.0
115	0.80512E 00	0.43155E 00	65.375	1587.479	0.0	0.0
116	0.69061E 00	0.89793E 00	66.000	1522.771	0.0	0.0
117	0.76010E 00	0.95083E 00	66.625	1559.873	0.0	0.0
118	0.81087E 00	0.58387E 00	67.250	1601.148	0.0	0.0
119	0.93936E 00	0.12834E 01	67.875	1520.002	0.0	0.0
120	0.97514E 00	0.10582E 01	68.125	1513.292	0.0	0.0
121	0.12804E 01	0.14995E 01	68.750	1556.103	0.0	0.0
122	0.11472E 01	0.88395E 00	69.375	1615.017	0.0	0.0
123	0.11551E 01	0.10817E 01	70.000	1577.443	0.0	0.0
124	0.10078E 01	0.10578E 01	70.625	1585.766	0.0	0.0
125	0.10030E 01	0.86938E 00	71.250	1581.018	0.0	0.0
126	0.94804E 00	0.91697E 00	71.875	1575.534	0.0	0.0
127	0.97922E 00	0.11513E 01	72.125	1552.062	0.0	0.0
128	0.10967E 01	0.12217E 01	72.750	1545.957	0.0	0.0
129	0.10147E 01	0.67110E 00	73.375	1533.522	0.0	0.0
130	0.91282E 00	0.84563E 00	74.000	1570.461	0.0	0.0
131	0.73453E 00	0.68686E 00	74.625	1551.752	0.0	0.0
132	0.77686E 00	0.79748E 00	75.250	1596.563	0.0	0.0
133	0.80794E 00	0.93948E 00	75.875	1513.448	0.0	0.0
134	0.10792E 01	0.15005E 01	76.125	1530.311	0.0	0.0
135	0.10689E 01	0.76665E 00	76.750	1574.107	0.0	0.0
136	0.11613E 01	0.12167E 01	77.375	1611.526	0.0	0.0
137	0.90880E 00	0.74311E 00	78.000	1535.376	0.0	0.0
138	0.94521E 00	0.87586E 00	78.625	1560.439	0.0	0.0
139	0.69608E 00	0.46926E 00	79.250	1586.200	0.0	0.0
140	0.65017E 00	0.60538E 00	79.875	1569.988	0.0	0.0
141	0.56465E 00	0.61930E 00	80.125	1563.728	0.0	0.0
142	0.71787E 00	0.92894E 00	80.750	1527.053	0.0	0.0
143	0.76479E 00	0.74613E 00	81.375	1550.394	0.0	0.0
144	0.74021E 00	0.54556E 00	82.000	1558.290	0.0	0.0
145	0.80531E 00	0.11242E 01	82.625	1607.981	0.0	0.0
146	0.85981E 00	0.90962E 00	83.250	1560.827	0.0	0.0
147	0.90481E 00	0.68056E 00	83.375	1559.392	0.0	0.0
148	0.76477E 00	0.70414E 00	84.125	1575.627	0.0	0.0
149	0.70875E 00	0.74156E 00	84.750	1549.083	0.0	0.0
150	0.82761E 00	0.10371E 01	85.375	1483.087	0.38906E 00	0.24461E 00
151	0.82026E 00	0.68210E 00	86.000	1544.235	0.0	0.0
152	0.11831E 01	0.18301E 01	86.625	1514.044	0.0	0.0
153	0.12986E 01	0.13837E 01	87.250	1550.278	0.0	0.0
154	0.12782E 01	0.62075E 00	87.875	1578.427	0.0	0.0
155	0.99320E 00	0.97516E 00	88.125	1572.090	0.0	0.0
156	0.11821E 01	0.19503E 01	88.750	1608.486	0.0	0.0
157	0.13929E 01	0.12534E 01	89.375	1576.387	0.0	0.0
158	0.13213E 01	0.76040E 00	90.000	1585.036	0.0	0.0
159	0.10156E 01	0.10329E 01	90.625	1608.400	0.0	0.0

160	0.91296E 00	0.94553E 00	91.250	1609.432	0.0		0.0
161	0.10852E 01	0.12771E 01	91.875	1572.416	0.0		0.0
162	0.96869E 00	0.68347E 00	92.125	1588.698	0.0		0.0
163	0.99684E 00	0.10300E 01	92.750	1575.751	0.0		0.0
164	0.78877E 00	0.65285E 00	93.375	1573.579	0.0		0.0
165	0.75771E 00	0.59030E 00	94.000	1571.648	0.0		0.0
166	0.55710E 00	0.42815E 00	94.625	1549.564	0.0		0.0
167	0.64229E 00	0.90842E 00	95.250	1533.949	0.0		0.0
168	0.57260E 00	0.38123E 00	95.875	1610.626	0.0		0.0
169	0.63987E 00	0.62997E 00	96.125	1615.133	0.0		0.0
170	0.62725E 00	0.87055E 00	96.750	1635.108	0.0		0.0
171	0.77751E 00	0.83200E 00	97.375	1621.734	0.0		0.0
172	0.77169E 00	0.61253E 00	98.000	1603.320	0.0		0.0
173	0.79594E 00	0.94329E 00	98.625	1536.563	0.0		0.0
174	0.89989E 00	0.11439E 01	99.250	1604.258	0.0		0.0
175	0.10149E 01	0.95770E 00	99.875	1559.206	0.0		0.0
176	0.10030E 01	0.90746E 00	100.125	1539.123	0.0		0.0
177	0.80903E 00	0.56194E 00	100.750	1552.783	0.0		0.0
178	0.76402E 00	0.82265E 00	101.375	1579.359	0.0		0.0
179	0.76715E 00	0.91684E 00	102.000	1563.938	0.0		0.0
180	0.89080E 00	0.93292E 00	102.625	1558.011	0.0		0.0
181	0.73460E 00	0.35464E 00	103.250	1576.868	0.0		0.0
182	0.71141E 00	0.84668E 00	103.875	1564.752	0.0		0.0
183	0.63308E 00	0.69792E 00	104.125	1610.192	0.0		0.0
184	0.77522E 00	0.78105E 00	104.750	1553.706	0.0		0.0
185	0.85996E 00	0.11009E 01	105.375	1554.280	0.0		0.0
186	0.98544E 00	0.10744E 01	106.000	1577.148	0.0		0.0
187	0.10656E 01	0.10217E 01	106.625	1596.773	0.0		0.0
188	0.10759E 01	0.11318E 01	107.250	1571.214	0.0		0.0
189	0.11197E 01	0.12056E 01	107.875	1582.733	0.0		0.0
190	0.10532E 01	0.82216E 00	108.125	1587.302	0.0		0.0
191	0.84821E 00	0.51687E 00	108.750	1551.387	0.0		0.0
192	0.68307E 00	0.71017E 00	109.375	1591.971	0.0		0.0
193	0.74664E 00	0.10129E 01	110.000	1605.593	0.0		0.0
194	0.78274E 00	0.62519E 00	110.625	1579.304	0.0		0.0
195	0.74767E 00	0.60495E 00	111.250	1579.157	0.0		0.0
196	0.67934E 00	0.80790E 00	111.875	1596.036	0.0		0.0
197	0.84177E 00	0.11125E 01	112.125	1545.204	0.0		0.0
198	0.99388E 00	0.10613E 01	112.750	1516.667	0.0		0.0
199	0.11316E 01	0.12209E 01	113.375	1531.079	0.0		0.0
200	0.10327E 01	0.81598E 00	114.000	1589.372	0.90085E 00		0.31433E 00
201	0.84985E 00	0.51263E 00	114.625	1603.560	0.0		0.0
202	0.68334E 00	0.72140E 00	115.250	1608.291	0.0		0.0
203	0.93904E 00	0.15831E 01	115.875	1604.180	0.0		0.0
204	0.12025E 01	0.13031E 01	116.125	1569.073	0.0		0.0
205	0.12532E 01	0.87351E 00	116.750	1559.190	0.0		0.0
206	0.99866E 00	0.81936E 00	117.375	1564.853	0.0		0.0
207	0.79878E 00	0.70348E 00	118.000	1607.788	0.0		0.0

352	0.58754E 00	0.89671E 00	200.750	1574.448	0.0	0.0
353	0.66019E 00	0.51978E 00	201.375	1585.029	0.0	0.0
354	0.65280E 00	0.54192E 00	202.000	1503.822	0.0	0.0
355	0.84573E 00	0.14755E 01	202.625	1556.801	0.0	0.0
356	0.10580E 01	0.11566E 01	203.250	1578.629	0.0	0.0
357	0.11580E 01	0.84203E 00	203.875	1563.658	0.0	0.0
358	0.11073E 01	0.13235E 01	204.125	1579.467	0.0	0.0

TAPE WAS READ 12 TIMES TO REPOSITION FOR NEXT CASE

```
C       MAIN PROGRAM
C
C        THIS PROGRAM CALCULATES A ROUGH DISTORTION INDEX FOR
C      THE J-85-GE-13 JET ENGINE USING DATA READ FROM A MAGNETIC TAPE
C      THE TAPE DATA CONSISTS OF THE FOLLOWING/ THERE ARE 15 EVENTS
C      ON THE TAPE. THE FIRST 4 EVENTS WERE CALIBRATION READINGS
C      THE LAST 11 WERE ACTUAL DATA READINGS. EACH EVENT CONSISTS
C      , ON THE TAPE , OF 64 LOGICAL RECORDS. EACH OF THESE
C      RECORDS CONSISTS OF OF 32 SETS OF 30 READINS. ONE FOR EACH
C      OF THE PROBES AT THE COMPRESSOR FACE. -HERE ARE NO TIME LABELS
C      ON THE TAPE AND TO USE THE TAPE A COUNTER MUST BE PROGRAMED
C      IN THE PROGRAM WHICH READS FROM THE TAPE IN ORDER TO IDENTIFY
C      WHICH CASE OF WHICH STALL EVENT IS BEING CALCULATED
C
C      ***************************************************
C
C        THIS PROGRAM IS DESIGNED TO TAKE THE DISTRIBUTIONS
C        OF TOTAL PRESSURE AT THE COMPRESSOR FACE AND FROM
C        THIS DATA CALCULATE THE DISTRIBUTION OF RADIAL
C        VORTICITY AND CICUMFERENTIAL VORTICITY AT THE FACE
C        OF THE COMPRESSOR.     THE INTERPOLATION SCHEME
C        USED  WAS DEVELOPED AT THE LEWIS RESEARCH CENTER OF
C      NASA.
C
C      ***************************************************
      INTEGER*2 TAPED,MCOUNT,CAL,A                                      VANN0001
      INTEGER*2 INTRIM                                                  VANN0002
      REAL KDM,PTKEEP(30)                                               VANN0003
      DIMENSION RADIAL(34),CIRCUM(60),YMEAN(448),YSTDV(448)             VANN0004
      DIMENSION PTHOLD(448),TIME(448)                                   VANN0005
      DIMENSION STALL1(2),STALL2(2)                                     VANN0006
      REAL*8 TITLE5(12)                                                 VANN0007
      DIMENSION ANGLE(20)                                               VANN0008
      DIMENSION THETA(20),PVORT(20,10),DPDTH(20,10),DPDR(20,10),        VANN0009
     1PCVORT(20,10),VORTRA(20,10),UZVORT(20,10),VORT(20, 0)             VANN0010
      DIMENSION PT(20,10),PP(20,10),RP(10),THETAO(10)                   VANN0011
      DIMENSION PO(10,10),POP(10,10),MCOUNT(10,10),DELTAP(10,10)        VANN0012
      DIMENSION TAPED(960)                                              VANN0013
      DIMENSION INTRIM(32,30)                                           VANN0014
      DIMENSION FACT(448),DFACT(448),RFACT(8)                           VANN0015
      DATA RADIAL,CIRCUM/34*0.0,60*0.0/                                 VANN0016
      DATA YMEAN,YSTDV/448*0.0,448*0.0/                                 VANN0017
      DATA RFACT/.95,.90,.85,.80,.70,.65,.60,.55/                       VANN0018
      DATA NAIX,NRIX/18,7/                                              VANN0019
      DATA RP/.27531,.41014,.59419,.73542,.85014,.95267,.99999/         VANN0020
      DATA GAMMA/1.4/                                                   VANN0021
      DATA NR/7/                                                        VANN0022
      DATA THETAO/-55.,0.,65.,120.,185.,240.,305.,360.,425./            VANN0023
```

```
      DATA NT/9/                                                        VANN0024
      DATA PI/3.14157/                                                  VANN0025
      DATA THETA/0.,20.,40.,60.,80.,100.,120.,140.,160.,180.,           VANN0026
     A200.,220.,240.,260.,280.,300.,340.,360. /                         VANN0027
      DATA TITLE4/'    '/                                               VANN0028
      DATA TITLE6 /'STAL'/                                              VANN0029
      B=72.0*10.0/3094.0                                                VANN0030
      CAL=4096                                                          VANN0031
      DO 17 N=1,9                                                       VANN0032
   17 THETAO(N)=THETAO(N)*PI/180.0                                      VANN0033
      DO 75 N=1,NAIX                                                    VANN0034
      ANGLE(N)=THETA(N)                                                 VANN0035
      THETA(N)=THETA(N)*PI/180.0                                        VANN0036
   75 CONTINUE                                                          VANN0037
C
CCC   THE FOLLOWING DO LOOP POSITIONS THE TAPE TO THE DESIRED
CCC   STARTING POINT. USE FORMULA NRUNS =(3*FIRST CASE NUMBER)*64
C
      NRUNS=4*64                                                        VANN0036
      DO 27 N=1,NRUNS                                                   VANN0037
      READ(4,105,END=1020,ERR=1021) TAPED                               VANN0038
   27 CONTINUE                                                          VANN0039
C
CCC   THE FOLLOWING CARD, 1008 CONTINUE, IS A SWITCHING POINT TO BE ENTERED
CCC   WHEN A NEW CASE IS TO BE CONSIDERED.
C
 1008 CONTINUE                                                          VANN0040
      READ(5,1010,END=1007) NRUN,NSTOP,STALL,PSTATC                     VANN0041
      READ(5,1003) TITLE5                                               VANN0042
      WRITE(6,1071) (TITLE5(I),I=1,6)                                   VANN0043
      ITIMES=0                                                          VANN0045
      SUM1=0.0                                                          VANN0046
      JTIMES=1                                                          VANN0047
      NMAP=-1                                                           VANN0048
      STALL2(1)=1.E20                                                   VANN0049
      STALL2(2)=0.0                                                     VANN0050
      NFACT=1                                                           VANN0051
C
CCC   THE VALUES OF STATIC PRESSURE AT EACH OF THE PROBES
CCC   ARE READ IN HERE
C
      DO 1 N=2,7                                                        VANN0052
    1 READ(5,103)(PO(N,J),J=1,7)                                        VANN0053
C
CCC   THE VALUES OF THE PRESSURES AT AN ANGLE OF 360 ARE
C      SET EQUAL TO THE PRESSURES AT AN ANGLE OF0
C     IN ORDER TO ASSURE THAT THE INTERPOLATION SCHEME
C     WILL BE SMOOTH
```

```
C
      DO 50 J=1,7                                                        VANN0341
      PO(9,J)=PO(3,J)                                                    VANN0054
      PO(1,J)=PO(7,J)                                                    VANN0055
   50 PO(8,J)=PO(2,J)                                                    VANN0056
      PSUM=0.0 D00                                                       VANN0057
      DO 2 N=2,7                                                         VANN0058
      DO 2 J=2,6                                                         VANN0059
    2 PSUM=PSUM+PO(N,J)                                                  VANN0060
      PAVE=PSUM/30.0D 00                                                 VANN0061
      DO 65 I=1,9                                                        VANN0062
      DO 65 J=1,7                                                        VANN0063
      POP(I,J)=PO(I,J)/PAVE                                              VANN0064
   65 CONTINUE                                                           VANN0065
C
CC      STATEMENT 100 US A SWITCHING POINT THAT CAN BE RETURNED TO
CC    IN ORDER TO CALCULATE VALUES OF VORTICITY FOR THE SAME
CC    STATIC PRESSURES BUT DIFFERENT DYNAMIC PRESSURES
CC    USED IN THE CALCULATION OF VORTICITY
C
  100 CONTINUE                                                           VANN0066
      NMAP=NMAP+2                                                        VANN0067
      READ(4,105,END=1024,ERR=1025) TAPED                                VANN0068
      ITIMES=ITIMES+1                                                    VANN0069
      DO 600 N=1,32                                                      VANN0070
      JUST=(N-1)*30+1                                                    VANN0071
      JEST=JUST+29                                                       VANN0072
      DO 600 J=JUST,JEST                                                 VANN0073
      KLAP=J-JUST+1                                                      VANN0074
      INTRIM(N,KLAP)=TAPED(J)                                            VANN0075
  600 CONTINUE                                                           VANN0076
      NCASE=1                                                            VANN0077
  700 DO 605 N=2,7                                                       VANN0078
      JUST=(N-2)*5+1                                                     VANN0079
      JEST=JUST+4                                                        VANN0080
      DO 605 J=JUST,JEST                                                 VANN0081
      KLAP=J-JUST+2                                                      VANN0082
      MCOUNT(N,KLAP)=INTRIM(NCASE,J)                                     VANN0083
  605 CONTINUE                                                           VANN0084
C     THE FOLLOWING CARDS, TO 500 WRITE ECHO CHECK THE VALUES OF TOTAL PRESSURE
CC    READ FROM THE TAPE.  DELETE IF NOT DESIRED.  INSERT AFTER 605 CONTINUE
C
      WRITE(6,213) NRUN,NMAP                                             VANN0085
      WRITE(6,209)                                                       VANN0086
      DO 500 I=2,7                                                       VANN0087
  500 WRITE(6,210)(MCOUNT(I,J),J=2,6)                                    VANN0088
      NCASE=NCASE+5                                                      VANN0089
      ICASE=NMAP                                                         VANN0090
```

```
      PTSUM=0.0                                                          VANN0091
      DO 4 I=2,7                                                         VANN0092
      DO 4 J=2,6                                                         VANN0093
      A=MCOUNT(I,J)-CAL                                                  VANN0094
      DELTAP(I,J)=A*8                                                    VANN0095
      PT(I,J)=PO(I,J)+DELTAP(I,J)                                        VANN0096
    4 CONTINUE                                                           VANN0097
      DELTAP(8,2)=DELTAP(2,2)                                            VANN0098
      DELTAP(8,6)=DELTAP(2,6)                                            VANN0099
      DO 53 I=2,8                                                        VANN0100
      PT(I,7)=PO(I,7)+DELTAP(I,6)                                        VANN0101
      PT(I,1)=PO(I,1)+DELTAP(I,2)                                        VANN0102
   53 CONTINUE                                                           VANN0103
      DO 51 J=1,7                                                        VANN0104
      PT(9,J)=PT(3,J)                                                    VANN0105
      PT(1,J)=PT(7,J)                                                    VANN0106
   51 PT(8,J)=PT(2,J)                                                    VANN0107
      DO 5 I=2,7                                                         VANN0108
      DO 5 J=2,6                                                         VANN0109
    5 PTSUM=PTSUM+PT(I,J)                                                VANN0110
      PTAVE=PTSUM/30.000 00                                              VANN0111
      XMACHP=UZMACH(PTAVE,PSTATC)                                        VANN0112
      DO 6 I=1,9                                                         VANN0113
      DO 6 J=1,7                                                         VANN0114
    6 PP(I,J)=PT(I,J)/PTAVE                                              VANN0115
      EXTERNAL SPLIN2,SPLIN1,F2,FX,FY                                    VANN0116
      CALL SPLIN2(THETAO,RP,PP,NT,NR)                                    VANN0117
      DO 82 I=1,NAIX                                                     VANN0118
      DO 82 J=1,NRIX                                                     VANN0119
      X=THETA(I)                                                         VANN0120
      Y=RP(J)                                                            VANN0121
      PVORT(I,J)=F2(X,Y)                                                 VANN0122
      DPDTH(I,J)=FX(X,Y)                                                 VANN0123
      DPDR(I,J)=FY(X,Y)                                                  VANN0124
   82 CONTINUE                                                           VANN0125
      DO 85 I=1,NAIX                                                     VANN0126
      DO 85 J=1,NRIX                                                     VANN0127
      PTSUB=PVORT(I,J)*PTAVE                                             VANN0128
      UZVORT(I,J)=UZPRIM(XMACHP,PTSUB,PSTATC,PTAVE)                      VANN0129
   85 CONTINUE                                                           VANN0130
      DO 86 I=1,NAIX                                                     VANN0131
      DO 86 J=1,NRIX                                                     VANN0132
      VORT(I,J)=(-1./(GAMMA*PVORT(I,J)*UZVORT(I,J)))*DPDR(I,J)           VANN0133
      VORTRA(I,J)=DPDTH(I,J)/(GAMMA*PVORT(I,J)*UZVORT(I,J)*RP(J))        VANN0134
      86 CONTINUE                                                        VANN0135
C
CC    USE ONE OF THE FOLLOWING THREE INDICES
C
```

```
C       START SHUMAKER INDEX                                                    VANN0135
C                                                                               VANN0136
        CALL SPLIN2(THETA,RP,VORT,NAIX,NR)                                      VANN0137
        FACT(NFACT)=0.                                                          VANN0138
        DO 799 NCOMP=1,30                                                       VANN0139
        XT=(NCOMP*12.0)*PI/180.0                                                VANN0140
        SPFACT=0.                                                               VANN0141
        DO 853 JFACT=1,4                                                        VANN0142
        XY=RFACT(JFACT)                                                         VANN0143
        PFACT=F2(XT,XY)                                                         VANN0144
        IF (PFACT .LT. 0.) PFACT=0.                                             VANN0145
        SPFACT=SPFACT+PFACT                                                     VANN0146
  853   CONTINUE                                                                VANN0147
        SFACTM=0.                                                               VANN0148
        DO 854 JFACT=5,8                                                        VANN0149
        XY=RFACT(JFACT)                                                         VANN0150
        FACTM=F2(XT,XY)                                                         VANN0151
        IF(FACTM .GT. 0.) FACTM=0.                                              VANN0152
        SFACTM=SFACTM+FACTM                                                     VANN0153
    854 CONTINUE                                                                VANN0154
        FACT(NFACT)=FACT(NFACT)+SPFACT-SFACTM                                   VANN0155
    799 CONTINUE                                                                VANN0156
        FACT(NFACT)=FACT(NFACT)/(8.0*30.0)                                      VANN0157
C                                                                               VANN0158
CC      END SHUMAKER INDEX                                                      VANN0159
CC      START DOWNS INDEX                                                       VANN0160
CC                                                                              VANN0161
CC      FIRST WORK ON (PTAVE-PT)/PTAVW COMPONENT                                VANN0162
C                                                                               VANN0163
        DO 1050 I=1,30                                                          VANN0164
        XT=FLOAT(I)*12.0*PI/180.0                                               VANN0165
        PFACT=0.0                                                               VANN0166
        DO 1051 J=1,7                                                           VANN0167
        XY=.25+FLOAT(J)*.1                                                      VANN0168
        PFACT=PFACT+1.0-F2(XT,XY)                                               VANN0169
  1051  CONTINUE                                                                VANN0170
        RADIAL(I)=PFACT                                                         VANN0171
  1050  CONTINUE                                                                VANN0330
        DO 1052 I=1,4                                                           VANN0172
        J=I+30                                                                  VANN0173
        RADIAL(J)=RADIAL(I)                                                     VANN0174
  1052  CONTINUE                                                                VANN0175
        DO 1053 I=1,30                                                          VANN0176
        PFACT=0.0                                                               VANN0177
        L=I+4                                                                   VANN0178
        DO 1054 J=I,L                                                           VANN0179
        PFACT=PFACT+RADIAL(J)                                                   VANN0180
  1054  CONTINUE                                                                VANN0181
```

```
      CIRCUM(I)=PFACT                                                   VANN0175
 1053 CONTINUE                                                          VANN0176
C
CC    NOW WORK ON RADIAL VORTEX COMPONENT
C
      CALL SPLIN2(THETA,RP,VORTRA,NAIX,NR)                              VANN0177
      DO 1055 I=1,30                                                    VANN0178
      XT=FLOAT(I)*12.0*PI/180.0                                         VANN0179
      PFACT=0.0                                                         VANN0180
      DO 1056 J=1,7                                                     VANN0181
      XY=.25+FLOAT(J)*.1                                                VANN0182
      PFACT=PFACT+F2(XT,XY)                                             VANN0183
 1056 CONTINUE                                                          VANN0184
      RADIAL(I)=PFACT                                                   VANN0185
 1055 CONTINUE                                                          VANN0186
      DO 1057 I=1,4                                                     VANN0187
      J=I+30                                                            VANN0188
      RADIAL(J)=RADIAL(I)                                               VANN0189
 1057 CONTINUE                                                          VANN0190
      DO 1058 I=1,30                                                    VANN0191
      PFACT=0.0                                                         VANN0192
      L=I+4                                                             VANN0193
      DO 1059 J=I,L                                                     VANN0194
      PFACT=PFACT+RADIAL(J)                                             VANN0195
 1059 CONTINUE                                                          VANN0196
      CIRCUM(I+30)=PFACT                                                VANN0197
 1058 CONTINUE                                                          VANN0198
C
CC    NOW ADD RADIAL AND PRESSURE COMPONENTS, SEARCH FOR LARGEST
C
      HOLD1=0.0                                                         VANN0199
      DO 1060 I=1,30                                                    VANN0200
      J=I+30                                                            VANN0201
      PFACT=CIRCUM(I)+CIRCUM(J)                                         VANN0202
      IF(PFACT.GT.HOLD1) HOLD1=PFACT                                    VANN0203
 1060 CONTINUE                                                          VANN0204
      FACT(NFACT)=HOLD1                                                 VANN0205
C
CC    END DOWNS INDEX
CC    START COMPUTATION OF PRATT & WHITNEY INDEX K(DM)
C
      CALL SPLIN2(THETAO,RP,PP,NT,NR)                                   VANN0206
      KDM=0.0                                                           VANN0207
      HOLD6=0.0                                                         VANN0208
      DO 1047 N=1,5                                                     VANN0209
      XY=.1375+FLOAT(N)*.1625                                           VANN0210
      HOLD1=0.0                                                         VANN0211
      HOLD2=1.E99                                                       VANN0212
```

```
      HOLD3=0.0                                                          VANN0213
      DO 1043 I=1,30                                                     VANN0214
      XT=(FLOAT(I)*12.0)*PI/180.0                                        VANN0215
      PTKEEP(I)=F2(XT,XY)                                                VANN0216
      PTKEEP(I)=PTKEEP(I)*PTAVE                                          VANN0217
      HOLD1=HOLD1+PTKEEP(I)                                              VANN0118
      IF(PTKEEP(I).GT.HOLD3) HOLD3=PTKEEP(I)                             VANN0219
      IF(PTKEEP(I).LT.HOLD2) HOLD2=PTKEEP(I)                             VANN0220
 1043 CONTINUE                                                           VANN0221
      HOLD1=HOLD1/30.0                                                   VANN0222
      DO 1044 I=1,30                                                     VANN0223
      IF(PTKEEP(I).GT.HOLD1) GO TO 1045                                  VANN0224
 1044 CONTINUE                                                           VANN0225
 1045 J=I+1                                                              VANN0226
      HOLD4=0.0                                                          VANN0227
      HOLD5=0.0                                                          VANN0228
      DO 1046 K=J,30                                                     VANN0229
      IF(PTKEEP(K).GT.HOLD1) HOLD4=0.0                                   VANN0230
      HOLD4=HOLD4+1.0                                                    VANN0231
      IF(HOLD4.GT.HOLD5) HOLD5=HOLD4                                     VANN0232
 1048 CONTINUE                                                           VANN0234
      DO 1046 K=1,I                                                      VANN0235
      IF(PTKEEP(K).GT.HOLD1) HOLD4=0.0                                   VANN0236
      HOLD4=HOLD4+1.0                                                    VANN0237
      IF(HOLD4.GT.HOLD5) HOLD5=HOLD4                                     VANN0238
 1046 CONTINUE                                                           VANN0239
      KDM=KDM+((HOLD3-HOLD2)/HOLD1)*(HOLD5*12.0*PI)/(180.0*XY)           VANN0240
      HOLD6=HOLD6+1.0/XY                                                 VANN0241
 1047 CONTINUE                                                           VANN0242
      KDM=50.0*KDM/HOLD6                                                 VANN0243
      FACT(NFACT)=KDM                                                    VANN0244
C
C     END PRATT AND WHITNEY DISTORTION INDEX
      PTHOLD(NFACT)=PTAVE                                                VANN0245
      TIME(NFACT)=NMAP*.125                                              VANN0246
      DFACT(NFACT)=FACT(NFACT)                                           VANN0247
C     START COMPUTATION OF MEAN,STD-DEV,DFACT(N),TEST FOR STALL WARNING
C
      IF(NFACT.LT.51) GO TO 1076                                         VANN0248
      DFACT(NFACT)=(FACT(NFACT)+FACT(NFACT-1)+FACT(NFACT-2))/3.0         VANN0249
      TEST=XMEAN+2.5*STDV                                                VANN0250
      IF(DFACT(NFACT).LT.TEST) GO TO 1076                                VANN0251
      WRITE(6,1074) TIME(NFACT)                                          VANN0252
 1074 FORMAT(' ',' *** STALL WARNING ***',3X,'TIME IS',F8.3/)            VANN0253
 1076 CONTINUE                                                           VANN0254
      SUM1=SUM1+FACT(NFACT)                                              VANN0255
      IF(JTIMES.LT.50) GO TO 1072                                        VANN0256
      XMEAN=SUM1/50.0                                                    VANN0257
```

```
      YMEAN(NFACT)=XMEAN                                                    VANN0258
      N=NFACT-49                                                            VANN0259
      JTIMES=JTIMES+1                                                       VANN0260
      SUM2=0.0                                                              VANN0331
      DO 1077 I=N,NFACT                                                     VANN0332
      SUM2=SUM2+(FACT(I)-XMEAN)**2                                          VANN0333
 1077 CONTINUE                                                              VANN0334
      STDV=SUM2/49.0                                                        VANN0335
      STDV=SQRT(STDV)                                                       VANN0336
      YSTDV(NFACT)=STDV                                                     VANN0337
      SUM1=0.0                                                              VANN0338
      JTIMES=0                                                              VANN0339
 1072 CONTINUE                                                              VANN0340
C
C       END COMPUTATION OF MEAN,STD-DEV,DFACT(N),TEST FOR STALL WARNING
      IF(NFACT.GE.NSTOP) GO TO 107                                          VANN0261
      NFACT=NFACT+1                                                         VANN0262
      IF (NCASE.GT. 32) GO TO 100                                           VANN0263
      NMAP=NMAP+5                                                           VANN0264
      GO TO 700                                                             VANN0265
  107 CONTINUE                                                              VANN0266
      WRITE(6,1075) STALL                                                   VANN0267
 1075 FORMAT(' ','  STALL OCCURRED AT TIME',F8.2/)                          VANN0268
      WRITE(6,1006) NRUN,PSTATC                                             VANN0269
      WRITE(6,1015) ITIMES                                                  VANN0270
      WRITE(6,1000)                                                         VANN0271
      DO 115 N=1,NSTOP                                                      VANN0272
      WRITE(6,216)N,DFACT(N),FACT(N),TIME(N),PTHOLD(N),YMEAN(N),YSTDV(N)    VANN0273
  115 CONTINUE                                                              VANN0274
C     START PLOT OF DFACT(N) V.S. TIME
C
      DO 1002 N=1,NSTOP                                                     VANN0275
      IF(DFACT(N).LT.STALL2(1)) STALL2(1)=DFACT(N)                          VANN0276
      IF(DFACT(N).GT.STALL2(2)) STALL2(2)=DFACT(N)                          VANN0277
 1002 CONTINUE                                                              VANN0278
      DIFF=STALL2(2)-STALL2(1)                                              VANN0279
      DIFF=DIFF/20.0                                                        VANN0280
      STALL2(1)=STALL2(1)+DIFF                                              VANN0281
      STALL2(2)=STALL2(2)-DIFF                                              VANN0282
      STALL1(1)=STALL                                                       VANN0283
      STALL1(2)=STALL                                                       VANN0284
      N=NSTOP                                                               VANN0285
      CALL DRAW(N,TIME,DFACT,1,0,TITLE4,TITLE5,0.,0.,0,0,1,1,8,8,1,L)       VANN0286
      CALL DRAW(2,STALL1,STALL2,3,0,TITLE6,TITLE5,0.,0.,0,0,0,0,8,12,       VANN0287
     11,L)                                                                  VANN0288
C
C     END PLOT OF DFACT(N) V.S. TIME
      IF(ITIMES.EQ.64) GO TO 1008                                           VANN0289
```

```
      ISTOP=64-ITIMES                                                   VANN0290
      DO 1042 I=1,ISTOP                                                 VANN0291
 1042 READ(4,105,END=1024,ERR=1025) TAPED                               VANN0292
      WRITE(6,1049) I                                                   VANN0293
      GO TO 1008                                                        VANN0294
  103 FORMAT(7F10.4)                                                    VANN0295
  105 FORMAT(4(20A2),16OA2)                                             VANN0296
  209 FORMAT(//,40X,'***INPUT CHECK***',//)                             VANN0297
  210 FORMAT(/,15X,5I10)                                                VANN0298
  213 FORMAT(//,15X,'****FOR RUN NUMBER',1X,I2,2X,'CASE NUMBER',1X,I4,'*VANN0299
     1***',///)                                                         VANN0300
  216 FORMAT(' ',I4,2E15.5,2F12.3,2E15.5)                               VANN0301
 1000 FORMAT(' ',//3X,'N',7X,'DFACT(N)',8X,'FACT(N)',8X,'TIME',7X,      VANN0302
     1'PTAVE',10X,'MEAN',9X,'STD-DEV',//)                               VANN0303
 1003 FORMAT(6A8)                                                       VANN0304
 1006 FORMAT(' ',/'  CASE NUMBER',I4,/'  AVERAGE STATIC PRESSURE IS',   VANN0305
     1F12.3//)                                                          VANN0306
 1010 FORMAT(2I5,2F10.2)                                                VANN0307
 1015 FORMAT(' ',' TAPE WAS READ',I3,' TIMES'/)                         VANN0308
 1049 FORMAT(' ',' TAPE WAS READ',I3,                                   VANN0309
     1' TIMES TO REPOSITION FOR NEXT CASE',/)                           VANN0310
 1020 WRITE(6,1022) N                                                   VANN0311
 1022 FORMAT(' ',' END OF TAPE WAS REACHED',/                           VANN0312
     1'  DO 27 N=1,NRUNS',/'  WHERE N=',I5)                            VANN0313
 1071 FORMAT(' ',//2X,6A8//)                                            VANN0314
      STOP                                                              VANN0315
 1021 WRITE(6,1023) N                                                   VANN0316
 1023 FORMAT(' ',' FORMAT ERROR ON TAPE',/'  DO 27 N=1,NRUNS',          VANN0317
     1/'  WHERE N=',I5)                                                VANN0318
      STOP                                                              VANN0319
 1024 WRITE(6,1026) NMAP                                                VANN0320
 1026 FORMAT(' ',' END OF TAPE WAS REACHED',/'  AFTER 100 CONTINUE',/   VANN0321
     1'  WHERE NMAP=',I5)                                               VANN0322
      STOP                                                              VANN0323
 1025 WRITE(6,1027) NMAP                                                VANN0324
 1027 FORMAT(' ',' FORMAT ERROR ON TAPE',/                              VANN0325
     1'  AFTER 100 CONTINUE',/'  WHERE NMAP=',I5)                       VANN0326
      STOP                                                              VANN0327
 1007 STOP                                                              VANN0328
      END                                                               VANN0329
C     FUNCTION UZMACH
      FUNCTION UZMACH(PTF,POF)
C
CC    THIS SUBROUTINE CALCULATES THE AXIAL MACH NUMBER
C
      G=1.4
      A=(G-1.0)/G
      B=2.0/(G-1.0)
```

```
      C=PTF/POF
      IF(C.LT.0.) C=-C
      UZMACH=B*((C**A)-1.0)
      IF(UZMACH.LT.0.0) GO TO 10                                        VANN
      UZMACH=SQRT(UZMACH)
      RETURN
   10 CONTINUE
   20 FORMAT(' ',/'  *** WARNING - PTAVE IS LESS THAN PAVE ***'/)       VANN
      UZMACH=-UZMACH                                                    VANN
      UZMACH=SQRT(UZMACH)                                               VANN
      RETURN                                                            VANN
      END                                                               VANN
C     FUNCTION UZPRIM
      FUNCTION UZPRIM(XM,PTF,POFA,PTFA)
C     THIS  SUBPROGRAM CALCULATES THE AXIAL VELOCITY TO BE
      A=PTFA-POFA
      B=(PTF-POFA)/A
      IF (B.LE. 0.0) GO TO 59
      C=SQRT(B)
      UZPRIM=XM*C
      RETURN
   59 UZPRIM=1.0
      RETURN
      END
C     SUBROUTINE SPLIN2
      SUBROUTINE SPLIN2(X,Y,Z,N,M)
      DIMENSION X(20),Y(20),Z(20,10),ZI(20),ZP(20)
      COMMON/SPLIN/N1,M1,X1(20),Y1(20),ZI(20,10),ZX(20,10),ZY(20,10),
     1 ZYX(20,10)
      COMMON /BNDRY/ BX1(20),BXN(20),JX,BY1(20),BYM(20),JY              5
      N1 = N                                                            6
      M1 = M                                                            7
      DO 10 I=1,N1                                                      8
   10 X1(I) = X(I)                                                      9
      DO 11 J=1,M1                                                     10
   11 Y1(J) = Y(J)                                                     11
      DO 12 I=1,N1                                                     12
      DO 12 J=1,M1                                                     13
   12 ZI(I,J) = Z(I,J)                                                 14
      DO 3 I=1,N1                                                      15
      DO 1 J=1,M1                                                      16
    1 ZI(J) = ZI(I,J)                                                  17
      CALL SPLIN1(Y1,ZI,M1,ZP,BY1(I),BYM(I),JY)                        18
      DO 2 J=1,M1                                                      19
    2 ZY(I,J) = ZP(J)                                                  20
    3 CONTINUE                                                         21
      DO 6 J=1,M1                                                      22
      DO 4 I=1,N1                                                      23
```

```
    4 ZI(I) = Z1(I,J)                                                      24
      CALL SPLIN1(X1,ZI,N1,ZP,BX1(J),BXN(J),JX)                            25
      DO 5 I=1,N1                                                          26
    5 ZX(I,J) = ZP(I)                                                      27
    6 CONTINUE                                                             28
      DO 9 J=1,M1                                                          29
      DO 7 I=1,N1                                                          30
    7 ZI(I) = ZY(I,J)                                                      31
      CALL SPLIN1(X1,ZI,N1,ZP,0.0,0.0,2)                                   32
      DO 8 I=1,N1                                                          33
    8 ZYX(I,J) = ZP(I)                                                     34
    9 CONTINUE                                                             35
      RETURN                                                               36
      END                                                                  37
C       BLOCK DATA
      BLOCK DATA                                                            1
      COMMON /BNDRY/ BX1(20),BXN(20),JX,BY1(20),BYM(20),JY                  2
      DATA BX1,BXN,BY1,BYM,JX,JY/80*0.0,2*2/                                3
      END                                                                   4
C       SUBROUTINE SPLIN1
      SUBROUTINE SPLIN1(X,Y,N,DY,B1,BN,J)
      DIMENSION X(1),Y(1),DY(1),A(20),B(20),C(20),D(20)                     2
      N1 = N-1                                                              3
      GO TO (4,5),J                                                         4
    4 B(1) = 1.0                                                            5
      C(1) = 0.0                                                            6
      D(1) = B1                                                             7
      A(N) = 0.0                                                            8
      B(N) = 1.0                                                            9
      D(N) = BN                                                            10
      GO TO 6                                                              11
    5 B(1) = 2.0                                                           12
      C(1) = 1.0                                                           13
      D(1) = 3.0*(Y(2)-Y(1))/(X(2)-X(1))-0.5*(X(2)-X(1))*B1                14
      A(N) = 1.0                                                           15
      B(N) = 2.0                                                           16
      D(N) = 3.0*(Y(N)-Y(N1))/(X(N)-X(N1))+0.5*(X(N)-X(N1))*BN             17
    6 DO 1 I=2,N1                                                          18
      A(I) = X(I+1)-X(I)                                                   19
      B(I) = 2.0*(X(I+1)-X(I-1))                                           20
      C(I) = X(I)-X(I-1)                                                   21
    1 D(I) = 3.0*(Y(I+1)*C(I)**2+Y(I)*(A(I)**2-C(I)**2)-Y(I-1)*A(I)**2)/   22
     *(C(I)*A(I))                                                          23
      D(1) = D(1)/B(1)                                                     24
      DO 2 I=2,N                                                           25
      B(I) = B(I)-A(I)*C(I-1)/B(I-1)                                       26
    2 D(I) = (D(I)-A(I)*D(I-1))/B(I)                                       27
      DY(N) = D(N)                                                         28
```

```
      DO 3 I=1,N1                                                        29
      K = N-I                                                            30
    3 DY(K) = D(K)-C(K)*DY(K+1)/B(K)                                     31
      RETURN                                                             32
      END                                                                33
C     FUNCTION F2
      FUNCTION F2(X1,Y1)
      COMMON/SPLIN/N,M,X(20),Y(20),Z(20,10),ZX(20,10),ZY(20,10),
     1 ZYX(20,10)
      G(FI,FI1,DFI,DFI1,DEL,S) = (2.0*(FI-FI1)+DEL*(DFI+DFI1))*(S/DEL)**.  4
     * 3 + (3.0*(FI1-FI)-DEL*(2.0*DFI+DFI1))*(S/DEL)**2 + DFI*S + FI       5
      IF(X1.LT.X(1))  WRITE (6,201)
      DO 1 I=2,N                                                         7
      K = I-1                                                            8
      IF(X1.LE.X(I))  GO TO 2                                            9
    1 CONTINUE                                                           10
      WRITE (6,202)
    2 IF(Y1.LT.Y(1))  WRITE (6,203)
      DO 3 J=2,M                                                         13
      L = J-1                                                            14
      IF(Y1.LE.Y(J))  GO TO 4                                            15
    3 CONTINUE                                                           16
      WRITE (6,204)
    4 DEL = X(K+1)-X(K)                                                  18
      S = X1-X(K)                                                        19
      FXJ = G(Z(K,L),Z(K+1,L),ZX(K,L),ZX(K+1,L),DEL,S)                   20
      FXJ1 = G(Z(K,L+1),Z(K+1,L+1),ZX(K,L+1),ZX(K+1,L+1),DEL,S)          21
      FYXJ = G(ZY(K,L),ZY(K+1,L),ZYX(K,L),ZYX(K+1,L),DEL,S)              22
      FYXJ1 = G(ZY(K,L+1),ZY(K+1,L+1),ZYX(K,L+1),ZYX(K+1,L+1),DEL,S)     23
      DEL = Y(L+1)-Y(L)                                                  24
      S = Y1-Y(L)                                                        25
      F2= G(FXJ,FXJ1,FYXJ,FYXJ1,DEL,S)                                   26
      RETURN                                                             27
  201 FORMAT (' **WARNING** X BELOW XMIN IN F2')
  202 FORMAT (' **WARNING** X ABOVE XMAX IN F2')
  203 FORMAT (' **WARNING** Y BELOW YMIN IN F2')
  204 FORMAT (' **WARNING** Y ABOVE YMAX IN F2')
      END                                                                28
C     FUNCTION FX
      FUNCTION FX(X1,Y1)
      COMMON/SPLIN/N,M,X(20),Y(20),Z(20,10),ZX(20,10),ZY(20,10),
     1 ZYX(20,10)
      G(FI,FI1,DFI,DFI1,DEL,S) = (2.0*(FI-FI1)+DEL*(DFI+DFI1))*(S/DEL)**   4
     * 3 + (3.0*(FI1-FI)-DEL*(2.0*DFI+DFI1))*(S/DEL)**2 + DFI*S + FI       5
      DG(FI,FI1,DFI,DFI1,DEL,S) = (6.0*(FI-FI1)+3.0*DEL*(DFI+DFI1))*      6
     * (S**2/DEL**3)+(6.0*(FI1-FI)-2.0*DEL*(2.0*DFI+DFI1))*(S/DEL**2)+    7
     * DFI                                                                8
      IF(X1.LT.X(1))  WRITE (6,201)
```

```
      DO 1 I=2,N                                                        10
      K = I-1                                                           11
      IF(X1.LE.X(I))  GO TO 2                                           12
    1 CONTINUE                                                          13
      WRITE (6,202)
    2 IF(Y1.LT.Y(1))  WRITE (6,203)
      DO 3 J=2,M                                                        16
      L = J-1                                                           17
      IF(Y1.LE.Y(J))  GO TO 4                                           18
    3 CONTINUE                                                          19
      WRITE (6,204)
    4 DEL = X(K+1)-X(K)                                                 21
      S = X1-X(K)                                                       22
      FXJ =DG(Z(K,L),Z(K+1,L),ZX(K,L),ZX(K+1,L),DEL,S)                  23
      FXJ1 =DG(Z(K,L+1),Z(K+1,L+1),ZX(K,L+1),ZX(K+1,L+1),DEL,S)         24
      FYXJ =DG(ZY(K,L),ZY(K+1,L),ZYX(K,L),ZYX(K+1,L),DEL,S)             25
      FYXJ1 =DG(ZY(K,L+1),ZY(K+1,L+1),ZYX(K,L+1),ZYX(K+1,L+1),DEL,S)    26
      DEL = Y(L+1)-Y(L)                                                 27
      S = Y1-Y(L)                                                       28
      FX =G(FXJ,FXJ1,FYXJ,FYXJ1,DEL,S)                                  29
      RETURN                                                            30
  201 FORMAT (' **WARNING** X BELOW XMIN IN FX')
  202 FORMAT (' **WARNING** X ABOVE XMAX IN FX')
  203 FORMAT (' **WARNING** Y BELOW YMIN IN FX')
  204 FORMAT (' **WARNING** Y ABOVE YMAX IN FX')
      END                                                               31
C     FUNCTION FY
      FUNCTION FY(X1,Y1)
      COMMON/SPLIN/N,M,X(20),Y(20),Z(20,10),ZX(20,10),ZY(20,10),
     1 ZYX(20,10)
      G(FI,FI1,DFI,DFI1,DEL,S) = (2.0*(FI-FI1)+DEL*(DFI+DFI1))*(S/DEL)**  4
     * 3 + (3.0*(FI1-FI)-DEL*(2.0*DFI+DFI1))*(S/DEL)**2 + DFI*S + FI      5
      DG(FI,FI1,DFI,DFI1,DEL,S) = (6.0*(FI-FI1)+3.0*DEL*(DFI+DFI1))*     6
     * (S**2/DEL**3)+(6.0*(FI1-FI)-2.0*DEL*(2.0*DFI+DFI1))*(S/DEL**2)+   7
     * DFI                                                               8
      IF(X1.LT.X(1))  WRITE (6,201)
      DO 1 I=2,N                                                        10
      K = I-1                                                           11
      IF(X1.LE.X(I))  GO TO 2                                           12
    1 CONTINUE                                                          13
      WRITE (6,202)
    2 IF(Y1.LT.Y(1))  WRITE (6,203)
      DO 3 J=2,M                                                        16
      L = J-1                                                           17
      IF(Y1.LE.Y(J))  GO TO 4                                           18
    3 CONTINUE                                                          19
      WRITE (6,204)
    4 DEL = X(K+1)-X(K)                                                 21
```

```
      S = X1-X(K)                                                                22
      FXJ = G(Z(K,L),Z(K+1,L),ZX(K,L),ZX(K+1,L),DEL,S)                           23
      FXJ1 = G(Z(K,L+1),Z(K+1,L+1),ZX(K,L+1),ZX(K+1,L+1),DEL,S)                  24
      FYXJ = G(ZY(K,L),ZY(K+1,L),ZYX(K,L),ZYX(K+1,L),DEL,S)                      25
      FYXJ1 = G(ZY(K,L+1),ZY(K+1,L+1),ZYX(K,L+1),ZYX(K+1,L+1),DEL,S)             26
      DEL = Y(L+1)-Y(L)                                                          27
      S = Y1-Y(L)                                                                28
      FY =DG(FXJ,FXJ1,FYXJ,FYXJ1,DEL,S)                                          29
      RETURN                                                                     30
  201 FORMAT (' **WARNING** X BELOW XMIN IN FY')
  202 FORMAT (' **WARNING** X ABOVE XMAX IN FY')
  203 FORMAT (' **WARNING** Y BELOW YMIN IN FY')
  204 FORMAT (' **WARNING** Y ABOVE YMAX IN FY')
      END                                                                        31
    1   358 202.4     1328.4
  SHUMAKER INDEX CASE 1
INDEX VERSUS TIME IN MILLISEC
1451.8626 1451.8626 1501.4536 1565.9396 1691.3519 1636.0002 1636.0002
1432.1083 1432.1083 1500.2638 1642.3657 1751.1593 1624.8854 1624.8854
1348.4871 1348.4871 1523.2363 1625.4640 1652.6589 1643.9811 1643.9811
1349.2036 1349.2036 1553.2164 1589.5275 1726.2901 1611.8961 1611.8961
1400.6433 1400.6433 1461.3921 1579.2414 1694.4100 1616.0150 1616.0150
1435.2196 1435.2196 1520.2648 1667.9199 1716.4504 1645.4229 1645.4229
    2   368 208.00    1276.08
  SHUMAKER INDEX CASE 2
INDEX VERSUS TIME IN MILLISEC
1573.6870 1573.6870 1726.2592 1316.6571 1811.3604 1612.9217 1612.9217
1465.3994 1465.4672 1436.3994 1500.1677 1504.0080 1385.4363 1385.4363
1296.0700 1296.0700 1384.6866 1409.6305 1348.5566 1357.8434 1357.8434
1309.0935 1309.8539 1398.9992 1339.2363 1402.2976 1324.9997 1324.9997
1463.2360 1463.2360 1449.3572 1515.3223 1513.9677 1391.9157 1391.9157
1553.3797 1553.3797 1732.7873 1881.5325 1879.5566 1668.1593 1668.1593
    3   377 213.00    1261.65
  SHUMAKER INDEX CASE 3                                                    VANN
INDEX VERSUS TIME IN MILLISEC
1352.5735 1352.5735 1483.1552 1627.2232 1678.0751 1471.2203 1471.2203
1334.7036 1334.7036 1451.0576 1650.1154 1678.7767 1445.2743 1445.2743
1247.3140 1247.3140 1453.5342 1628.1685 1592.5815 1455.9492 1455.9495
1243.6065 1243.6065 1489.2230 1603.8788 1692.1094 1440.0514 1440.0514
1316.9534 1316.9534 1430.3291 1623.6453 1679.3486 1428.3880 1428.3880
1335.7982 1335.7982 1420.8764 1594.0617 1614.2237 1462.3357 1462.3357
    4   372 210.00    1306.14
  SHUMAKER INDEX CASE 4                                                    VANN
INDEX VERSUS TIME IN MILLISEC
1418.6713 1418.6713 1451.3273 1496.1226 1636.4836 1694.7291 1694.7291
1405.7029 1405.7029 1455.3907 1582.1733 1728.5401 1707.2761 1707.2761
1332.2134 1332.2134 1466.2439 1543.9504 1596.4982 1698.0627 1698.0627
1327.9400 1327.9400 1499.4361 1527.1232 1712.7689 1689.3808 1689.3808
```

1380.1003 1380.1003 1415.6249 1512.6465 1642.7130 1662.2269 1662.2269
1408.8715 1408.8715 1480.7541 1601.7068 1690.2755 1716.8910 1716.8910
5 363 205.00 1398.16
SHUMAKER INDEX CASE 5
INDEX VERSUS TIME IN MILLISEC VANN
1666.3963 1666.3963 1818.7818 1880.3162 1797.6624 1701.9778 1701.9778
1650.9715 1650.9715 1687.4623 1719.4293 1646.9066 1529.7500 1529.7500
1480.0871 1480.0871 1638.8161 1590.4541 1464.1510 1474.1094 1474.1094
1494.1638 1494.1638 1665.2950 1533.3213 1525.9700 1449.4757 1449.4757
1645.3537 1645.3537 1683.7746 1736.0452 1664.0994 1540.4989 1540.4989
1668.2337 1668.2337 1826.3712 1925.8472 1886.1694 1770.9925 1770.9925
6 370 209.00 1414.82
SHUMAKER INDEX CASE 6
INDEX VERSUS TIME IN MILLISEC VANN
1811.9492 1811.9492 1781.3304 1761.5481 1832.5313 1734.1839 1734.1839
1741.2417 1741.2417 1683.4219 1686.3353 1681.5245 1577.0834 1577.0834
1556.9346 1556.9346 1641.4994 1597.2332 1507.5959 1526.1772 1526.1772
1571.8806 1571.8806 1668.0477 1535.6991 1519.2911 1475.0460 1475.0460
1711.2081 1711.2081 1705.9681 1705.6459 1690.6859 1466.9770 1466.9770
1799.8426 1799.8426 1800.2906 1862.1638 1882.4060 1786.8659 1786.8659
7 368 208.00 1223.74
SHUMAKER INDEX CASE 7
INDEX VERSUS TIME IN MILLISEC VANN
1422.1162 1422.1162 1439.2698 1419.0266 1469.0105 1464.4571 1464.4571
1431.6963 1431.6963 1440.9129 1483.1376 1528.8176 1462.4760 1462.4760
1325.8011 1325.8011 1479.1578 1526.1029 1482.7464 1496.2387 1496.2387
1384.8700 1384.8700 1504.5912 1455.3979 1497.4205 1401.9850 1401.9850
1353.8376 1353.8376 1390.9558 1445.3746 1514.3536 1372.8690 1372.8690
1395.5898 1395.5898 1453.3537 1532.9523 1513.4343 1486.9039 1486.9039
8 381 215.00 1275.78
SHUMAKER INDEX CASE 8
INDEX VERSUS TIME IN MILLISEC
1610.4857 1610.4857 1540.1321 1429.5918 1478.7769 1450.1652 1450.1652
1566.5557 1566.5557 1482.6532 1444.2306 1462.8061 1388.0021 1388.0021
1469.8713 1469.8713 1572.0943 1550.3664 1499.9551 1483.7517 1483.7517
1480.0896 1480.0896 1591.2217 1487.9798 1569.1219 1477.9966 1477.9966
1527.6853 1527.6853 1538.1792 1519.7454 1558.0728 1490.1230 1490.1230
1563.0083 1563.0083 1551.9307 1562.2764 1545.3166 1493.1624 1493.1624
9 381 215.0 1228.35
SHUMAKER INDEX CASE 9
INDEX VERSUS TIME IN MILLISEC
1553.8450 1553.8450 1497.5656 1409.2474 1415.9325 1435.1545 1435.1545
1500.7617 1500.7617 1440.8035 1412.4173 1427.1435 1404.1285 1404.1285
1460.6806 1460.6806 1519.6373 1474.7046 1409.8072 1489.9129 1489.9129
1421.3395 1421.3395 1501.7105 1386.1011 1436.9948 1414.5874 1414.5874
1510.9540 1510.9540 1475.4631 1446.2818 1452.1193 1441.4677 1441.4677
1520.0437 1520.0437 1487.9260 1472.1736 1436.1367 1480.7629 1480.7629
10 381 215.00 1311.14

SHOMAKER INDEX CASE 10
INDEX VERSUS TIME IN MILLISEC

1659.8524	1659.8524	1581.4581	1485.3308	1502.2312	1527.4028	1527.4028	
1634.4444	1634.4444	1553.4664	1528.4449	1566.6509	1540.6557	1540.6557	
1544.5883	1544.5883	1599.2734	1559.0421	1497.2378	1572.8865	1572.8865	
1542.5131	1542.5131	1613.7859	1497.9520	1580.1966	1549.9193	1549.9193	
1608.3188	1608.3188	1556.2557	1531.5645	1552.0794	1546.5919	1546.5919	
1644.8383	1644.8383	1589.8199	1573.5388	1541.3947	1574.3154	1574.3154	
11	361	215.00	1302.02				

SHOMAKER INDEX CASE 11
INDEX VERSUS TIME IN MILLISEC

1806.9933	1806.9933	1704.8856	1606.3607	1648.3197	1643.6256	1643.6256	
1568.5534	1568.5534	1508.1514	1510.9038	1556.8626	1528.7295	1528.7295	
1457.4135	1457.4135	1493.6862	1403.6432	1294.8883	1329.9399	1329.9399	
1459.3828	1459.3828	1488.9837	1321.7753	1361.5658	1295.1818	1295.1818	
1558.7431	1558.7431	1513.1456	1513.3343	1574.5348	1528.9388	1528.9388	
1789.8077	1789.8077	1720.4731	1699.3338	1678.7796	1674.8125	1674.8125	

LIST OF REFERENCES

1. Farmer, C. J., Inlet Distortion, Vorticity, and Stall in an Axial Flow Compressor, Master's Thesis, Naval Postgraduate School, Monterey, Calif., 1972.

2. AIAA Paper No. 72-1116, A New Approach To Distortion Induced Compressor Stall--Vorticity Maps, by Lt. Clinton Farmer, Lcdr. Michael Iverson, and Allen Fuhs, 1972.

3. Shoemaker, J. E., An Analysis of the Effects of Instantaneous Vorticity on Compressor Performance, Master's Thesis, Naval Postgraduate School, Monterey, Calif., 1973.

4. Downs, C. P., A Rational Basis for Circumferential Distortion Index Formulation, Master's Thesis, Naval Postgraduate School, Monterey, Calif., to be published 1974.

5. NASA Lewis Research Center Technical Memorandum, Instantaneous Distortion in a Mach 2.5, 40-percent-Internal-Contraction Inlet and its Effect on Turbojet Stall Margin, by Paul L. Burstadt and James E. Calogeras, to be published 1974.

6. AIAA Paper No. 71-667, Instantaneous and Dynamic Analysis of Supersonic Inlet-Engine Compatibility, by J. E. Calogeras, P. L. Burstadt, and R. E. Coltrin, 1971.

7. AIAA Paper No. 73-1316, The Effect of Inlet Temperature and Pressure Distortion on Turbojet Performance, by W. M. Braithwaite, E. J. Graber, Jr., and C. M. Mehalic, 1973.

8. AGARD NATO Lecture Series No. 53, Ref 6, Dynamic Characteristics of Engine Inlets, by D. Zonars, 1972.

9. NASA Edwards Technical Note No. D-7328, Steady-State and Dynamic Pressure Phenomena in the Propulsion System of an F-111A Airplane, by F. W. Burcham, Jr., D. L. Hughes, and J. K. Holzman, 1973.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Chairman, Department of Aeronautics, Code 57Be Naval Postgraduate School Monterey, California 93940	1
4.	LTjg James E. Shoemaker 113 Norton Street Bennington, Vermont 05201	1
5.	Professor Allen E. Fuhs, Code 57 Fu Department of Aeronautics Naval Postgraduate School Monterey, California 93940	10
6.	LT John L. Vann 1840 Lynnhaven Rd. Ft. Worth, Texas 76103	3
7.	Professor M. F. Platzer, Code 57Pl Department of Aeronautics Naval Postgraduate School Monterey, California 93940	1
8.	Mr. Joe Boytos Naval Air Propulsion Test Center Trenton, New Jersey 08628	1
9.	Dr. Herbert Mueller, Code 310A Naval Air Systems Command Washington, D. C. 20360	1
10.	Dr. Frank Tanczos, Code 03 Naval Air Systems Command Washington, D. C. 20360	1
11.	Mr. Karl Guttman, Code 330 Naval Air Systems Command Washington, D. C. 20360	1

12. Dr. H. O. Johnson, Code 330 — 1
Naval Air Systems Command
Washington, D. C. 20360

13. Mr. Robert Brown, Code 536 — 1
Naval Air Systems Command
Washington, D. C. 20360

14. Dr. Ralph Roberts — 1
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

15. Mr. Eric Lister — 1
R. & T. Division
Naval Air Propulsion Test Center
Trenton, New Jersey 08628

16. Mr. Albert Martino — 1
R. & T. Division
Naval Air Propulsion Test Center
Trenton, New Jersey 08628

17. Mr. James Patton, Jr. — 1
Office of Naval Research
Arlington, Virginia 22218

18. Mr. Ivan Bush — 1
AFAPL
WPAFB, Ohio 45433

19. M. l'Ingenieur en Chef Marc Pianko — 1
Service Technique Aeronautique
4 Avenue de la Porte d'Issy
75 Paris 15eme FRANCE

20. Mr. J. Surugue — 1
Directeur, Energie et Propulsion
ONERA
29 Avenue de la Division Leclerc
92 Chatillon-sous-Bagneux, FRANCE

21. Dr. John Dunham — 1
National Gas Turbine Establishment
Pyestock
Farnbourough Hants GREAT BRITAIN

22. Professor Kuhl — 1
D. V. L.
505 Porz Wahn
Linder Hohe
Allemagne GERMANY

23. Mr. Clifford Simpson — 1
AFAPL/TB
Wright-Patterson A.F.B., Ohio 45433

24. Professor Gordon Oates — 1
University of Washington
Seattle, Washington 98105

25. Professor Robert Goulard — 1
Director, Project SQUID
Purdue University
Lafayette, Indiana 47907

26. Mr. J. F. Chevalier — 1
SNECMA
Centre d'Essais de Villaroche
77 Moissy-Cramayel FRANCE

27. Mr. M. Van Staveren — 1
Institute for Applied Research TNO
Post bus 406
Delft NETHERLANDS

28. Mr. Hill Barrett — 1
Detroit Diesel Allison
General Motors Corp.
Indianapolis, Indiana 46206

29. Professor Antonio Ferri — 1
Department of Aeronautics and Astronautics
School of Engineering and Science
New York University
Bronx, New York 10453

30. Mr. Elmer G. Johnson — 1
Director, Fluid Dynamics Facilities Research Laboratory
USAF Aerospace Research Laboratories
Wright-Patterson A.F.B., Ohio 45433

31. Dr. A. A. Mikolajczak — 1
Pratt and Whitney Aircraft
East Hartford, Conn. 06108

32. Dr. Peter Tramm — 1
Detroit Diesel Allison
General Motors Corp.
Indianapolis, Indiana 46206

33. Professor Duncan Rannie — 1
California Institute of Technology
Pasadena, California 91109

34. Professor Jack Kerrebrock — 1
Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, Massachusetts 02138

35. Professor George Serovy — 1
Iowa State University
Ames, Iowa 50010

36. Dr. Gary R. Ludwig — 1
Aerodynamics Research
Cornell Aeronautical Laboratory, Inc.
Buffalo, New York 14221

37. Mr. James E. Calogeras — 1
NASA Lewis Research Center
Cleveland, Ohio 44135

38. Dr. Gunnar Broman — 1
Vice President, Engineering
VOLVO Flygmotor
Trollhattan, SWEDEN

39. Mr. Robert Zalis — 1
MZ 240 GF
1000 Western Avenue
Lynn, Massachusetts 01910

40. Mr. Paul H. Kutschenreuter, Jr. — 1
Mail Drop E 198
General Electric Company
Cincinnati, Ohio 45215

41. Mr. David Jamison — 1
General Electric Company
P.O. Box 2143
Kettering Branch
Dayton, Ohio 45429

42. Prof. Jacques Valensi — 1
Director Institut de Mecanique des Fluides
1 'Universite d'Aix-Marseille
Marseille, FRANCE

43. Professor Jacques Chauvin — 1
Von Karman Institute for Fluid Mechanics
72 Chaussee de Waterloo
1640 Rhode-St-Genese BELGIUM

44. Mr. Marvin F. Schmidt — 1
Turbine Engine Division
AFAPL
Wright-Patterson A.F.B., Ohio 45433

45. Mr. J. W. McBride 1
General Electric Company
Evandale, Ohio 45215

46. Dr. Leroy H. Smith, Jr. 1
General Electric Company
Evandale, Ohio 45215

47. Professor B. Lakshminarayana 1
MIT Gas Turbine Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02138

48. Professor Jean Louis 1
MIT Gas Turbine Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02138

49. Dr. F. O. Carta 1
United Aircraft Research Labs.
United Aircraft Corporation
400 Main Street
East Hartford, Connecticut 06108

50. Mr. Norman Cotter 1
Pratt and Whitney Florida Research Center
West Palm Beach, Florida 33402

51. Dr. George L. Mellor 1
Princeton University
Forrestal Campus
Princeton, New Jersey 08540

52. Mr. Stan Ellis 1
Pratt and Whitney Florida Research Center
West Palm Beach, Florida 33402

53. Mr. David Bowditch 1
NASA Lewis Research Center
Cleveland, Ohio 44135

54. Professor Frank Marble 1
California Institute of Technology
Pasadena, California 91109

55. Professor Bruce A. Reese 1
School of Mechanical Engineering
Purdue University
Lafayette, Indiana 47907

56. Professor T. C. Adamson, Jr. 1
Dept. of Aerospace Engineering
University of Michigan
Ann Arbor, Michigan 48103

57. Professor W. R. Sears 1
University of Arizona
Tucson, Arizona 85721

58. Professor J. E. McCune 1
M.I.T. - 37 - 391
Cambridge, Massachusetts 02139

59. Dr. Jack Nielsen 1
Nielsen Engineering and Research, Inc.
850 Maude Avenue
Mountain View, California 94040

60. W. F. O'Brien 1
Mechanical Engineering Dept.
Virginia Polytechnic Institute and State
University
Blacksburg, Virginia 24061

61. Dr. W. Heiser 1
AFAPL
Wright-Patterson A.F.B., Ohio 45433

62. CAPT Barry Brownstein 1
Air Force Aero-Propulsion Laboratory
Wright-Patterson A.F.B., Ohio 45433

63. Mr. Paul L. Burstadt 1
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio 44135

64. Lcdr. C. Downs 1
6200 N.W. 8th Street
Oklahoma City, Oklahoma 73127

153708

Thesis
V184 Vann
c.1 Formulation and comparison of instantaneous distortion indices for assessing compressor stall.